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CLIMATE SMART FORTALEZA

Minor Field Study

Submitted by

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Executive summary

With the urban population growing exponentially the challenges associated with urban development are numerous. The urban heat island effect, rising energy demands and floods are only a few of the problems that large cities face today. With climate change it is becoming urgent to build climate smart cities. The objective of this research project is to identify how the design of a city, based on the height-to-width ratio of buildings and streets (referred to as aspect ratio), street orientation and vegetation, can improve thermal comfort and reduce energy demands. The project also investigates if a 10-year rainfall can be retained through the use of floodplains.

The city chosen for this paper is Fortaleza, a densely populated city, located near the Equator in northeastern Brazil where the climate is hot and humid. Fortaleza is of interest because a large part of the city consists of densely spaced high-rise towers divided by narrow streets and minimal vegetation which is representative for many cities in Brazil. The district of Meireles, a part of the city located next to the northern shore, was chosen as a reference area for the study, referred to as Model 1. Model 1 is compared to a new area design, referred to as Model 2. The climatic and thermal comfort study was conducted through simulations in ENVI-MET and a shading analysis in Ecotect. The outdoor thermal comfort was calculated as Predicted Mean Vote, PMV. The storm-water study was conducted by mapping the catchment area and identifying the 10-year rainfall event.

The simulations of aspect ratio in ENVI-MET showed wind speeds that were inconsistent with previous research. An aspect ratio of 1.5, based on previous research, was used because it would optimize wind flow in the streets. It is possible that an optimal aspect ratio could be higher than 1.5, regarding PMV, due to increased shading from buildings. Two different street orientations were compared: one parallel to the eastern wind and one with a 30 degree tilt to the south. The street parallel to the wind was found to have slightly higher wind speed. Combination of grass and trees decreased air temperature and MRT but reduced wind speed. The average PMV value in the area decreased from 3.3 without vegetation to 2.4 with both grass and trees. Despite the significant decrease in wind speed when using trees in Model 2, the wind speed is still higher in Model 2 than in Model 1. The two different street orientations with vegetation showed no difference in wind speed, air temperature or PMV, indicating that there is no conflict in designing for both thermal comfort and natural indoor ventilation. The estimation of cooling degree days from the resulting lower outdoor air temperatures show potential of significant reduction in energy use by smart microclimatic design.

The average floodplain depth in the vegetated areas in Model 2 was required to be 2.4 m to retain the runoff volume from the full catchment area from a 10-year rainfall. Retaining only the runoff volume from Model 2 itself the average floodplain depth was required to be 0.6 m. The results indicate that it is possible to retain the runoff volume from a 10-year rainfall when storm water management is implemented in all parts of the catchment area.

Key Words: *Urban Design, Microclimate, Global Warming, Climate Smart Cities, Sustainable cities, Fortaleza, Brazil, Hot humid climate, Storm water management, Space cooling, Cooling degree days.*

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Nomenclature and Abbreviations

H/W – Height to width ratio or Aspect Ratio,

GC – Ground Coverage ratio

UHI – Urban Heat Island

CBD – Central Business District

MRT – Mean Radiant Temperature

UCL – Urban Canopy Layer

RH – Relative Humidity

RS – Roughness Sublayer

1 Introduction

1.1 Background

A few of the problems large cities face today are the urban heat island effect, air pollution, flood exposure and increasing energy demands. With climate change as one of our generation´s major global issues, scientists are predicting more extreme weather in the future with more intensive droughts, storms, floods and extreme temperatures. The *urban* population of the world is expected to increase from today's 3.9 billion to about 6.3 billion in 2050 (UN, 2009) and most of the expansion will take place in developing countries, such as Brazil. Brazil is of additional interest because of its expanding economy. This will mean an even higher impact on the climate as Brazil's energy demand grows. Buildings use approximately 40-50 % globally of all electricity for space heating or cooling today (IEA, 2014). More energy is used globally on cooling than heating (Svensk Fjärrvärme, 2015). According to the IEA (2014) the global energy consumption for space cooling increased by 60 % during 2000-2010. IEA predicts that the cooling demand in Latin America, China, India and ASEAN will increase with more than 600 % until 2050. To meet the increased cooling demand passive solutions are essential in future sustainable cities. Like most of Brazil, Fortaleza is located in a tropical zone, and thus a lot of energy is needed for cooling. Fortaleza was chosen as a reference city because of its high building density and lack of vegetation which is common in Brazil. The project "Climate Smart Fortaleza" is meant to tackle or highlight many of these issues. With climate change and the expansion of cities increasing exponentially, it is becoming more and more urgent to build and redesign cities to climate smart cities; cities with better air-quality, milder temperatures, that consume less energy and are resilient to floods.

The microclimate aspect of urban planning has been known for quite some time, but has not had a significant impact on building regulations and is unfortunately not commonly considered when designing urban areas (Ng, 2010). A microclimate is a local atmospheric zone with a different climate with respect to the surroundings, can constitute a large area such as a desert or forest, or a small-scale area of a few square meters, for example a small square within a city. When designing cities, focus is often on designing houses to protect the people from the outside environment. Little thought is being put into designing the outdoor area to improve the local climate conditions. Perhaps it has been thought that people spend most of their time indoors, when in fact, city people spend a lot of their time outdoors in the tropics.

The way cities are constructed have a direct effect on the microclimate in the city and is in turn very important with respect to how areas are used by its inhabitants. Although this project does not deal with transportation issues, the microclimate has an impact on how people choose to move within the city. A well designed area in terms of microclimate can promote walking and biking, compared to a poorly designed microclimate where the inhabitants are more likely to use the transportation of cars and buses - which often run on fossil fuels.

Most cities today are designed primarily for houses and the accessibility of cars. They are constructed with heavy materials such as asphalt and concrete, materials that are absorbing large amounts of heat. With the knowledge of today, microclimates can be manipulated to create better and healthier environments for humans while improving the energy performance of the surrounding buildings.

1.2 Purpose

This paper will investigate how street orientation, aspect ratio and vegetation, separately and combined, affect the microclimatic factors (wind speed, air temperature and mean radiant temperature) and the thermal comfort in Fortaleza, Brazil. The purpose is also to find out if, and how, designing for indoor cross-ventilation, the thermal comfort outdoors, expressed in Predicted Mean Vote Index (PMV), will be affected. The climatic and thermal comfort conditions in a part of the city district Meireles, referred to as Model 1, will be investigated and compared to a hypothetical new area design, Model 2, located in the same place.

The project also aims to investigate the current conditions regarding storm water in Fortaleza and if the vegetated areas in the new design can be used as floodplains to retain a 10-year rainfall.

1.3 Method overview

The climatic and thermal comfort study was conducted through simulations in ENVI-MET and through a shading analysis in Ecotect. ENVI-MET was calibrated by customizing the input data so that the output results of air temperature and relative humidity was consistent with the climatic data for Fortaleza. Thermal comfort was measured in Predicted Mean Vote, PMV. The storm-water study was conducted by mapping the catchment area and identifying the 10-year rainfall event.

1.4 Hypothesis

The hypotheses of this thesis are:

- An optimal aspect ratio and street orientation, in terms of increasing wind speed and decreasing solar radiation, combined with vegetation can be used to improve the thermal comfort in Fortaleza, Brazil.
- A low aspect ratio of buildings will have the highest wind velocities due to low obstruction of the wind flow and a high mixing of air between the urban canopy layer and the urban sub-layer, but the highest air temperature and mean radiant temperature due to a high influx of solar radiation.
- When choosing between a higher wind speed and increased aspect ratio for more shading, a higher wind speed is probably preferred. This is because of the fact that wind has a significant cooling effect and because increased aspect ratio is probably not leading to a lot more shade at mid-day, due to Fortaleza´s proximity to the equator.
- A street orientation where the main streets are parallel to the eastern wind is likely to significantly increase the wind speed compared to the current conditions.
- Using a street orientation with a 30 degree tilt to the south from the east-west direction will have a negative effect on the wind speed. The average values of air temperature and mean radiant temperature in the area will be unaffected compared to having parallel streets. Despite an increase of shade on the northern building façades there will be an equal increase of solar radiation on the southern façades.
- Grass will have no effect on wind speed but will decrease the air temperature due to evaporation and a lower thermal mass. Grass will also decrease the mean radiant temperature due to a decrease of long wave radiation from the ground.
- Trees are likely to have a negative effect on wind speed due to wind obstruction of the tree crowns and tree trunk. This effect is likely to be small because the trees are high and have a leafless base.
- A low aspect ratio combined with vegetation and a street orientation with parallel streets to the eastern winds is believed to be the best scenario. The same scenario but with a street orientation of 30 degrees to the south is likely to have a higher PMV value but still significantly better compared to the current conditions
- It will be unrealistic to retain a 10 year rainfall from the whole catchment area in the vegetated areas of Model 2, used as floodplains, due to the magnitude of the rainfalls. It is more likely that the volume from only the area of Model 2 could be retained.

1.5 About Fortaleza

Fortaleza is the fifth biggest city in terms of population in Brazil (OPOVO, 2015) and is known as a business city with a lot of high rise buildings in the Central Business District. It is located adjacent to the Atlantic Ocean to the east (Figure 1).

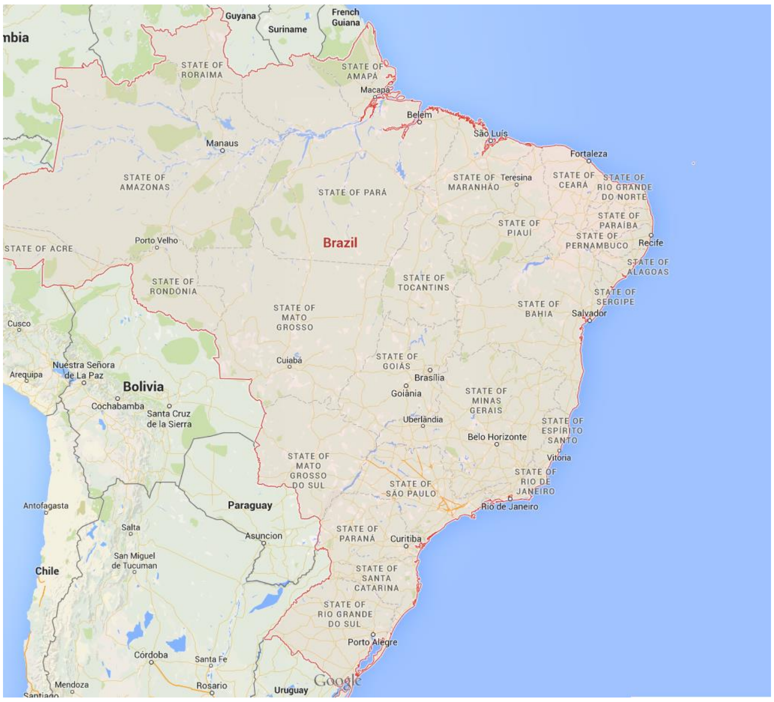


Figure 1. Map of Brazil (Google maps)

There are approximately 2.5 million people residing in Fortaleza as of 2014 (IBGE, 2015) with a high population density of approximately 8100 people/km^2.

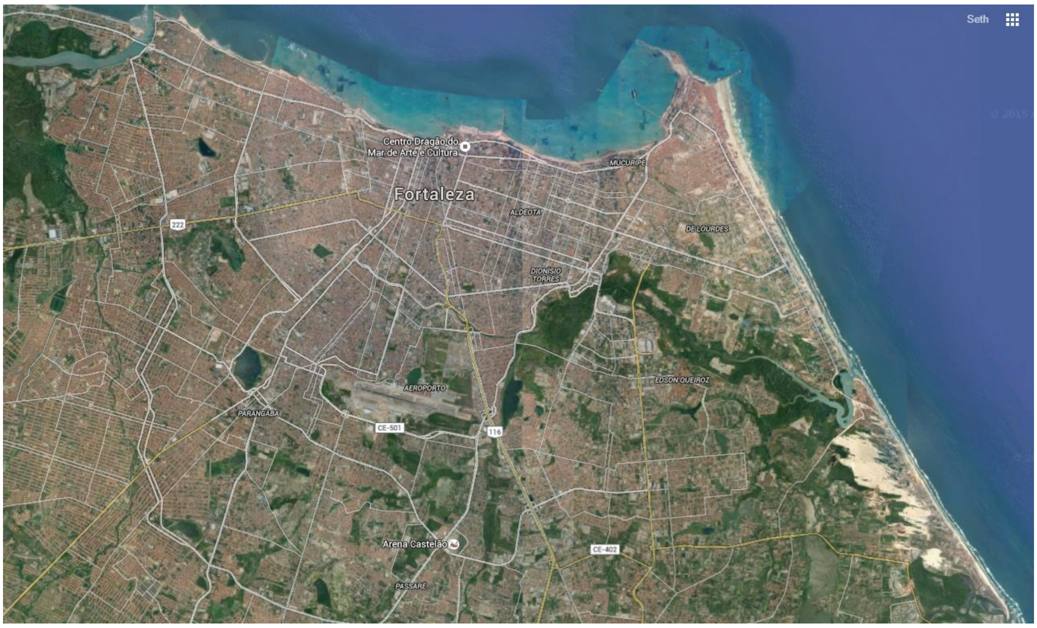


Figure 2. Map of Fortaleza, Brazil (Google maps).

Meireles is a central area with a lot of high-rise buildings close to the ocean (Figure 3). The buildings in the area are blocking a large part of the eastern trade winds. The small amount of trees offer no or little shade for pedestrians.

Figure 3*. Area of Meireles, Fortaleza (Google maps).*

The main street is oriented approximately 10° north to the most common wind direction of Fortaleza with trees providing little or no shade (Figure 4). The streets are straight with widths of 10 to 30 meters. High aspect ratios are common (Figure 5).

Figure 4. One of the major streets in the area. The trees in the middle of the street are providing little or no shade for pedestrians. (Photo: Seth von Dardel, 2015)

Figure 5. High buildings and narrow streets for many of the side streets. (Photo: Seth von Dardel, 2015)

1.6 Climate of Fortaleza

Fortaleza has a “Tropical wet and dry climate” also known as a ”Tropical savanna climate” referred to as hot and humid climate in this report. With an average temperature of 27.1 C throughout the year the seasons do not vary as much as in a temperate climate. However, the rain season from February to May is locally referred to as “winter” accompanied by heavy rainfalls during March and April in particular.

Meteorological data was provided from two different weather stations in Fortaleza: The weather station at Federal University of Ceará (3.7416°S, 38.5390°W) (and the weather station at Pinto Martin airport (3.7791°S, 38.5408°W). Wind and rain data was acquired from the station of the Federal University of Ceará. Air temperature, solar radiation, sunshine duration, relative humidity and monthly rainfalls was acquired from the weather station at Pinto Martin.

1.6.1 Air Temperature

The coldest month of the year is June with an average air temperature of 26.3 degrees. The warmest month of the year is December with an average air temperature of 28.0 degrees (Figure 6).

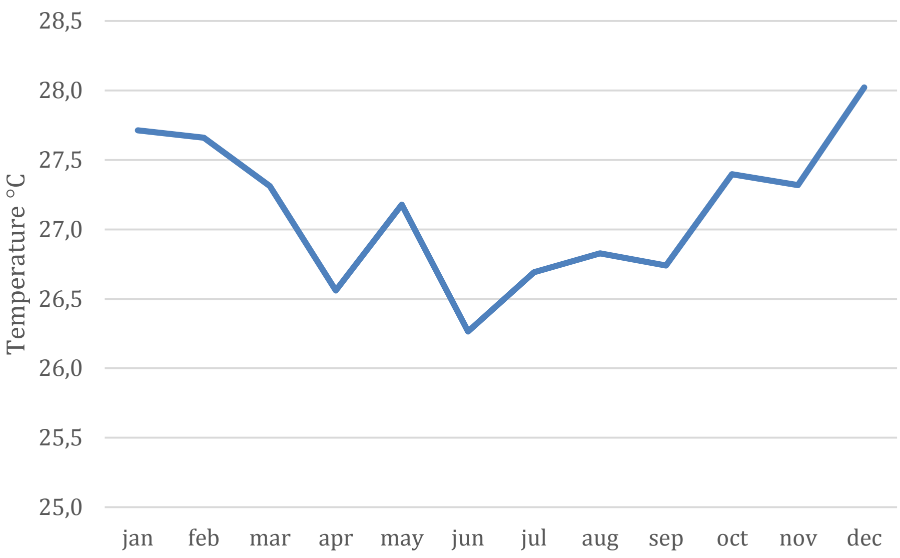


Figure 6. Average air temperature in Fortaleza, Brazil during 2000-2009, (Meteotest, 2009).

1.6.2 Humidity

April is the peak of Fortaleza´s rain season and has the highest average relative humidity at 84.3%. October has the lowest RH at 70.4% during the dry season. The two warmest months December and November also have a similar RH of 72.7% and 72.8% respectively, see Figure 7.

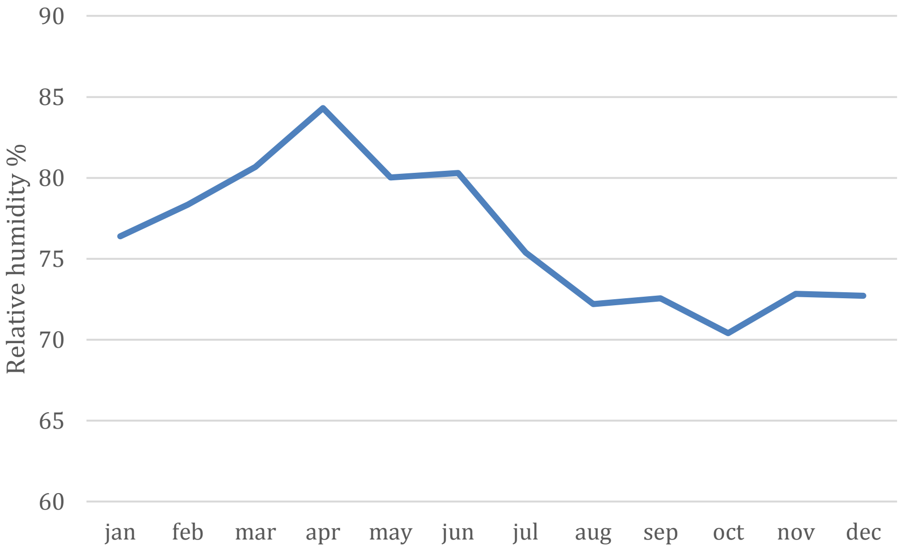


Figure 7. Average RH in Fortaleza during 2000-2009, (Meteotest, 2009).

1.6.3 Sun hours and radiation

October has the largest amount of sun hours: 9.2 h/day. November and September have 9.1 h/day and December has 8 h/day. Mars has the lowest amount of sun hours with 4.9 h/day (Figure 8).

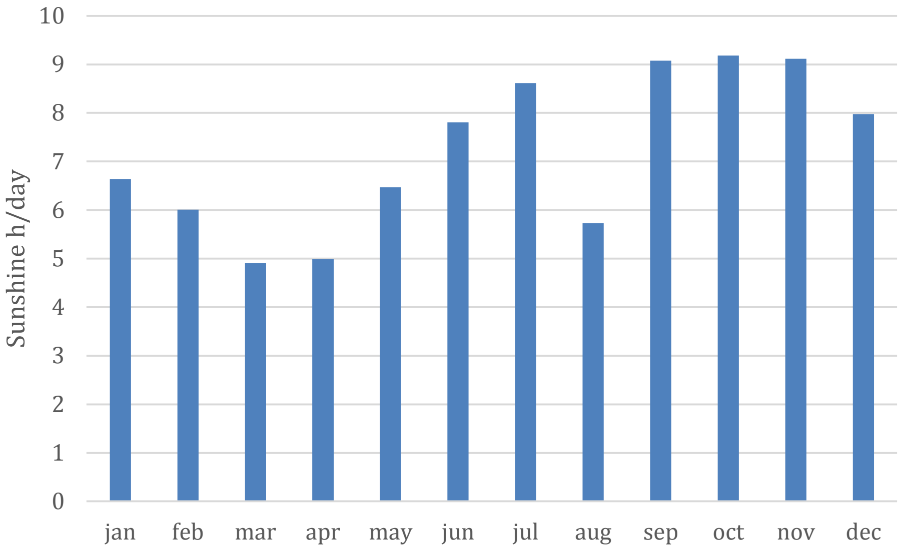


Figure 8. Average sunshine duration in Fortaleza during 2000-2009, (Meteotest, 2009).

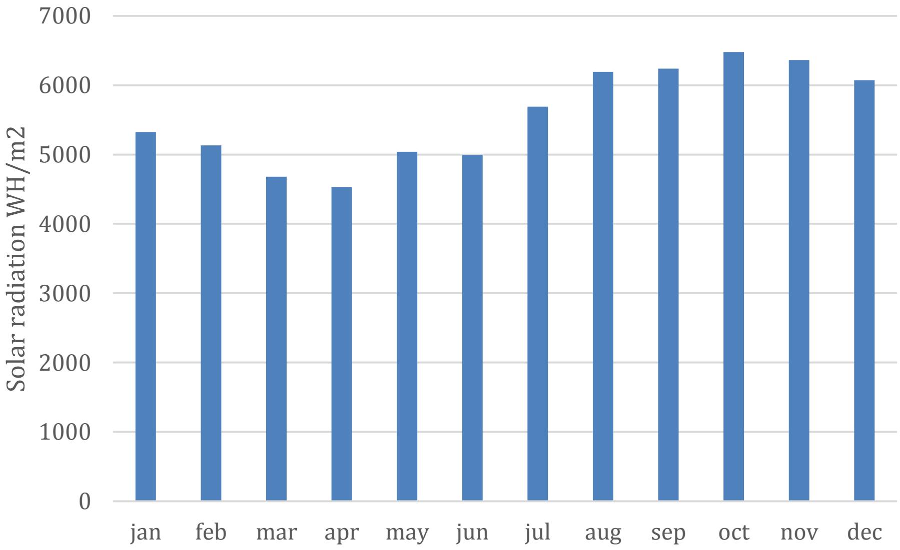


Figure 9 Average global solar radiation on a horizontal surface in Fortaleza during 2000-2009, (Meteotest, 2009).

1.6.4 Wind characteristics

Figure 10 shows the wind directions in Fortaleza during a whole year. The majority of the wind are trade winds that comes from the east and south east (Noaa, 2015). The average wind speed from the east throughout the year is 4.14 m/s (Figure 10). The wind data was taken from the Federal University of Ceará located about 5 km inland.

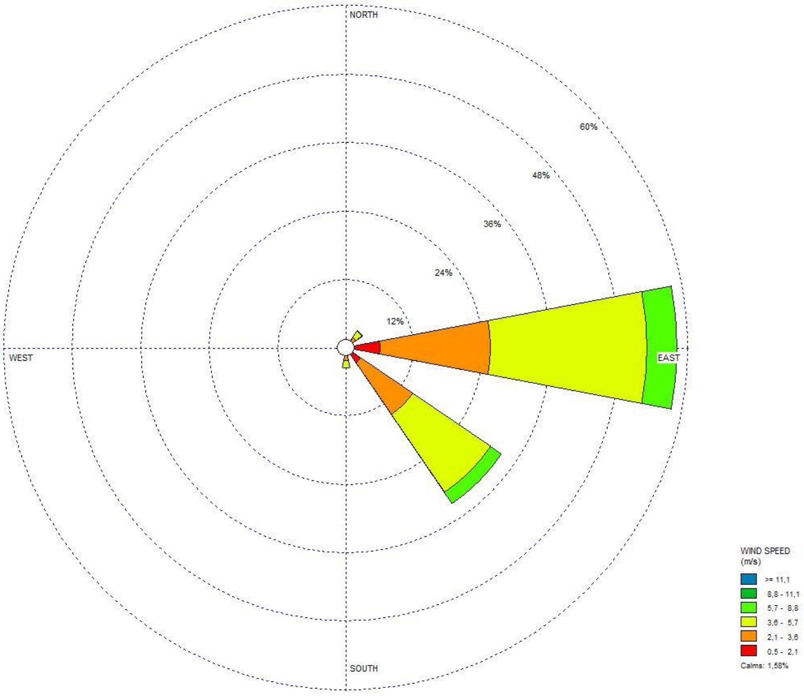


Figure 10. Wind rose for Fortaleza, Brazil, during a year (INDM, 2014)

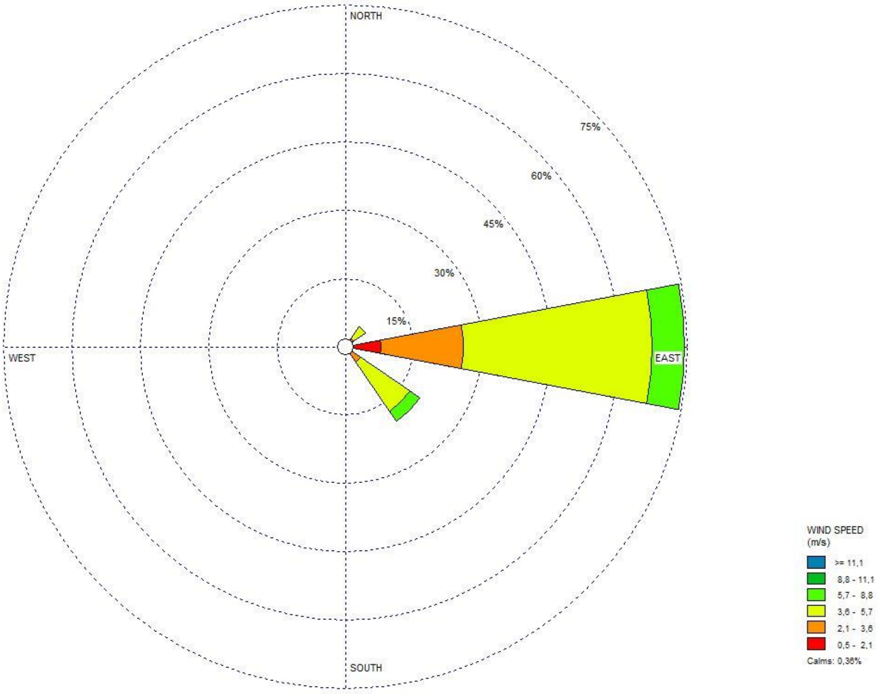


Figure 11. Wind rose from Fortaleza for the month of December (INDM, 2014)

Figure 11 shows the wind distribution of December. The second most dominant wind direction throughout the year and also during December month is from the South East (SE). Approximately 33% of all the winds during the year comes are SE.

1.6.5 Rain

The rain season hits it peak in April with an average rainfall of 242 mm. March is the second wettest month with an average of 132 mm rain. In October there is only 1 mm of rain and December has 11 mm of rain (Figure 12).

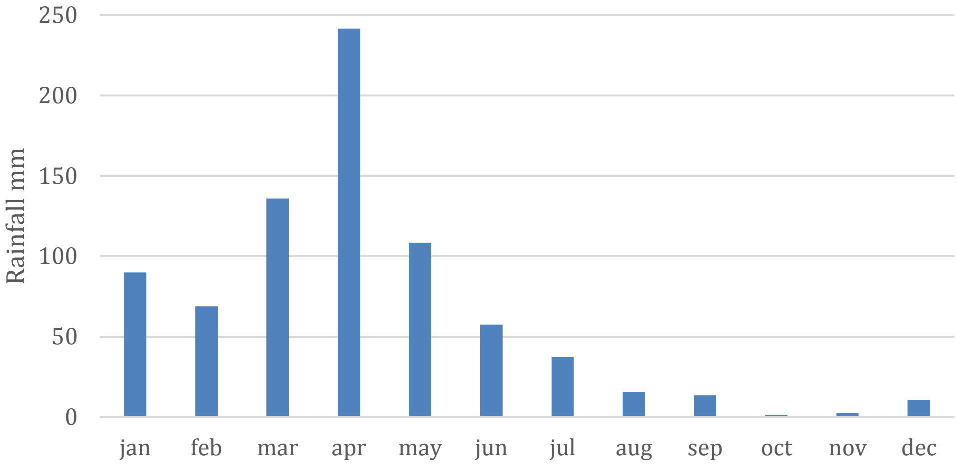


Figure 12. Average rainfall in mm in Fortaleza during 2000-2009, (Meteotest, 2009)

1.6.6 Storm water

In the part of the city of Fortaleza which was investigated in this project almost no infiltration surfaces could be found. Most of the area consists of impermeable rooftops, roads and pavements as can be seen in Figure 13.

Figure 13. Picture from Meireles, Fortaleza. (Photo: Seth von Dardel, 2015)

The lack of infiltration surfaces means that most of the storm water ends up as sewage water. In Meireles, storm water management consists of directing the storm water through drain pipes directly into the ocean, two of them which are located on the beach (Figure 14). The sand on the beach is quickly eroding during a rainfall in large part due to the storm water outlets. By releasing the storm water straight into the ocean without any treatment means that the beaches and the ocean becomes polluted. After a rain fall, the water on the beach is muddy and mixed with different kinds of trash from the urban area.

Figure 14. Storm water outlet pipes located on the adjacent beach. (Photos: Seth von Dardel, 2015)

The drainage pipes in Meireles are not dimensioned to handle large rainfalls. Pictures was taken during a rain fall in February 2015 (Figure 15 and Figure 16. Shortly after the rainfall had started, many parts of the area were flooded and it was difficult to use the walkways.

Figure 15. Flooded streets in Meireles. (Photos: Seth von Dardel, 2015)

Figure 16. Flooded walkway. (Photo: Seth von Dardel, 2015)

2 Theoretical concepts

2.1 Thermal Comfort

The thermal comfort is a combination of different external climatic parameters such as wind speed, air temperature, humidity and solar radiation. Other variables such as activity, clothing etc. also have a large impact. Some thermal indexes try and take into account of almost all of these variable´s whilst certain indexes are simplified to only a few. A selection of thermal indexes are described in more detail at the end of the chapter. There is usually more to take into consideration when measuring thermal comfort outdoors since there is seldom a steady-state of heat exchange. Typically the outdoors is more dynamic and therefore more unpredictable. The importance of thermal comfort is evident; many studies show that e.g. office performance and productivity drops with thermal discomfort (Kosonen & Tan, 2004). But more importantly, too high temperatures can have a negative impact on the wellbeing of people or even be severely dangerous (Abdel-Ghany et al, 2013).

Studies on the effect of air speed on comfort shows that when the air temperature is below 33°C the wind has a cooling effect due to a higher convective heat loss from the body (Givoni, 1998). Givoni also states that between 33-37°C the increase of air speed does not significantly affect the thermal comfort but may have a cooling effect due to the removal of skin wetness. The wind speed may have a negative impact on the thermal comfort when temperatures exceed 37°C since the rate of heating of the body is increased. However, it is not certain whether or not the net effect is negative or positive since the wind will decrease the skin wetness (Givoni, 1998).

One factor that has a major impact on the thermal comfort outdoors is the mean radiant temperature, MRT (Ng, 2010). MRT is defined as the uniform temperature of an imaginary enclosure in which radiant energy exchange with the body equals the radiant exchange in the actual non-uniform enclosure (Erell et al, 2011). If the MRT exceeds the body skin temperature, a person is subject to a net heat gain and vice versa. The experience of thermal comfort is depending on both the air temperature and the temperature of the surrounding surfaces. A person in an urban canyon is exposed to both short-wave radiation, from diffuse and direct sunlight, and long-wave radiation, from building and street surfaces. Thus the MRT is dependent on the amount of sunlight and the urban material, mass and color. A study in Singapore, which has a similar climate, found that the acceptable operative temperature for outdoor urban environments is between 26.3 °C and 31.7 °C (Yang et al, 2012). The operative temperature is the mean value of the air temperature and the MRT.

The thermal comfort zone is dynamic, and is affected by air temperature, wind speed, solar radiation and humidity and is illustrated as a zone rather than a specific point with an optimal temperature (Figure 17).

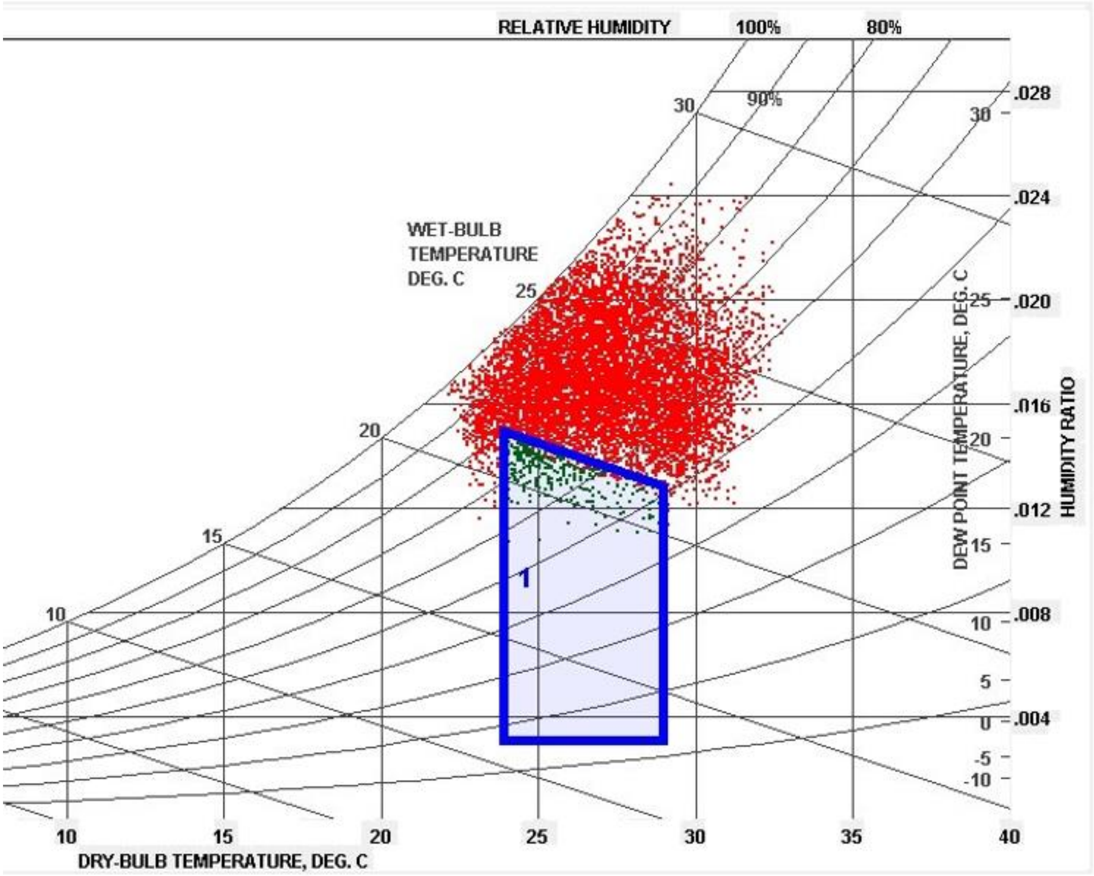


Figure 17. The psychometric chart shows how the outside air temperature and humidity affect the thermal comfort in Fortaleza, made in Climate Consultant 6.0 (ENERGY DESIGN TOOLS, 2015).

The psychometric chart (Figure 17) shows that only 3.5 % of the hours during a year are located in the thermal comfort zone according to the ASHRAE standard with an air temperature comfort zone between 24 °C and 28 °C.

It is also worth mentioning that the thermal comfort zone changes with season. In other words, the human body adapts to the environment surrounding (Givoni, 1998). This is a very important fact to take into consideration when designing in climates with very distinct seasons. Since Fortaleza is located close to the equatorial line the climate is not subject to any significant variation over the year. Another important aspect that has to be taken into consideration is that many of the thermal comfort indices are made in Europe or America (Givoni, 1998). Studies have shown that warmer countries often have a higher comfort zone than countries in temperate climates which is a phenomenon known as heat acclimatization (Givoni, 1998).

The climatic requirements of the thermal comfort zone indoors can be achieved by mechanically using an air conditioner (AC). The use of AC will lower the indoor air temperature but has a side effect of releasing heat to the outside environment. Fortaleza is a dense city and many buildings are using AC which are producing a large amount of heat, further heating the streets of Fortaleza. Studies have shown that a comfortable microclimate outdoors increases time spent outdoors thus minimizing the time indoors which in turn leads to a lower use of heating and cooling (Erell et al, 2011). It may be unavoidable using AC in places with hot air temperatures, but it is possible to lower the number of cooling degree days by smart microclimatic design and passive energy solutions. Cooling degree days (CDD) are an easy way of approximating the amount of energy needed for space cooling of a building (BizEE, 2015). The base temperature is set as a reference outdoor temperature for at which above this threshold the building needs cooling. Every degree above the base temperature is considered one CDD. Since the cooling load is dependent on the outside temperature the CDD is proportional to the cooling load, thus CDD is a simple quantification of the amount of energy that buildings at a specific location need for cooling during a period. Cooling degree days are only a rough estimate of the energy demand for space cooling since the method does not necessarily consider specific building insulation etc.

2.1.1 Thermal comfort indices

There are many ways to measure thermal comfort. Thermal comfort indices were created to quantify thermal comfort to gain a better understanding of how to design for better urban- and indoor climates. Thermal comfort indices vary between being specialized on indoor- and outdoor climates and different climate zones and some have more complicated formulas when taking clothing and activity into account. The following thermal comfort indices are based on the heat balance equation of the human body and the four environmental factors affecting the thermal comfort: wind speed, humidity, mean radiant temperature and air temperature.

2.1.1.1 Predicted Mean Vote, PMV

PMV is one of the most utilized thermal comfort indices. It is created for measuring thermal comfort indoors because it is limited to steady-state conditions which is difficult to achieve outdoors (Johansson, Urban Thermal Comfort in the Tropics, 2015) The method takes clothing and activity into account which can be varied depending on e.g. location and the hour of the day. PMV calculates the percentage of dissatisfied people and is expressed on a scale from -3 to 3 where -3 is cold, 0 is neutral and 3 is hot. While PMV is designed for indoor purposes, it has been used in outdoor studies as well but has been found to overestimate the thermal perception, resulting in a PMV value outside of the scale (Johansson, 2015).

2.1.1.2 Physiological equivalent temperature, PET

PET is defined as the air temperature, related to given standard indoor, core and skin temperatures, at which the body maintains the same heat balance. Expressed in degrees Celsius, PET is one of the most popular indices to use in outdoor conditions where, at a moderate level of human activity, it has been shown to successfully predict the thermal comfort (Johansson, Urban Thermal Comfort in the Tropics, 2015).

2.1.1.3 Universal thermal climate index – UTCI

The newly developed UTCI is expressed in degrees Celsius as the air temperature of the reference environment which according to the model produces an equivalent dynamic physiological response (Johansson, Urban Thermal Comfort in the Tropics, 2015). The index, which is designed for outdoors, is flexible and can be used in all climate types and seasons of the year.

2.1.2 Thermal Comfort of Fortaleza

A recent study shows that Fortaleza has a general thermal discomfort between 09:00-17:00 (Zanella et al, 2010). The most critical thermal discomfort is recorded at 14:00-15:00 for all areas. However the thermal comfort is acceptable during early mornings and at night (Zanella et al, 2010). Zanella et al. emphasizes that the government should work for a better urban design with large open green spots, wind tunnels and plantation of large trees (Zanella, 2012). One of the few places in the city that has a comfortable microclimate during 09:00-17:00 is the municipality which is located along the eastern beach. This beach is directly exposed to the eastern wind. Most of the other beaches around the city faces north and this is also where the population density is at its highest. Many of the places along the northern shore have almost no wind flow and the high air temperatures cause thermal distress. Many locations experience a thermal discomfort between 08:00-18:00.

2.2 Urban design and microclimate

The microclimate design process is very dynamic and is depending on the type of climate in the area. In a hot humid climate the urban design criteria's are often characterized by a "single design day" since seasonal variations are very small (Schiller & Evans, 1998). Two of the main design criteria for a hot humid city are maximizing wind speed and minimizing direct solar radiation which results in a cooling effect (Schiller & Evans, 1998). Compared to a temperate climate where the opposite is true; minimizing cold wind flow and maximizing sun radiation are key solutions to get a warmer outside environment (Johansson, 2015). Schiller & Evans (1998) emphasizes the importance of microclimate design in the urban planning phase since retrofitting is difficult and costly. An "energy-wasteful town plan" won't be overcome by more efficient insulation in the existing buildings.

2.2.1 Canyon geometry

An urban canyon is defined as a street with a certain height (H) of the buildings, length (L) of the block and width (W) of the street (Figure 18).

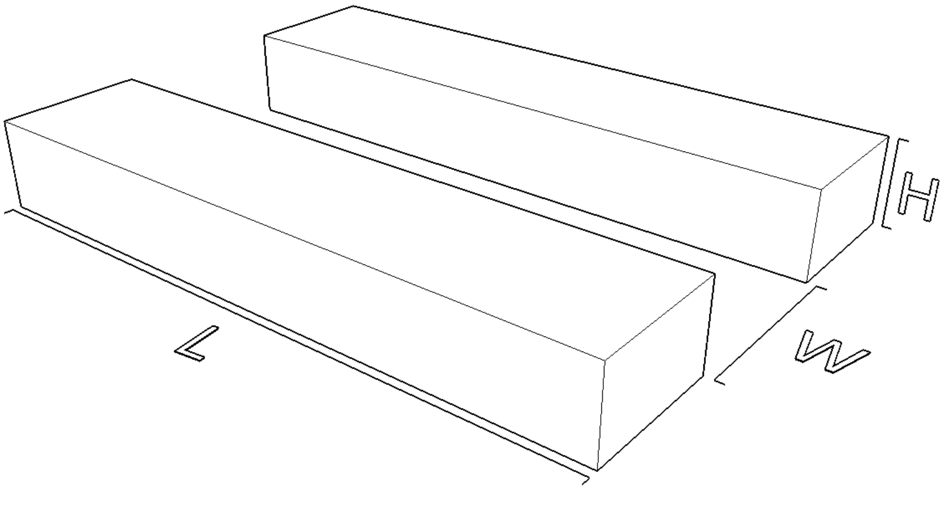


Figure 18. The geometry of an urban canyon

These are important features of the urban canyon since the Height-to-Width (H/W) ratio, also known as aspect ratio, will affect both wind flow and shading along the street. High buildings shade a large portion of the ground and a lot of the solar radiation can be reflected or absorbed by roofs (Niachou & Santamouris, 2005). Higher aspect ratio can induce a “mutual shading effect” where buildings cast shade on adjacent buildings (Maleki, 2011). However, a too high aspect ratio may affect the mixing between the different air layers above (Roughness sub-layer) and below (Urban Canopy Layer) the roof top.

If the streets that are perpendicular to the prevailing wind flow have an aspect ratio above 0.7 a skimming effect may occur where the air ventilation is inhibited between the roughness sub-layer (RSL) and urban canopy layer (UCL) (Figure 19).

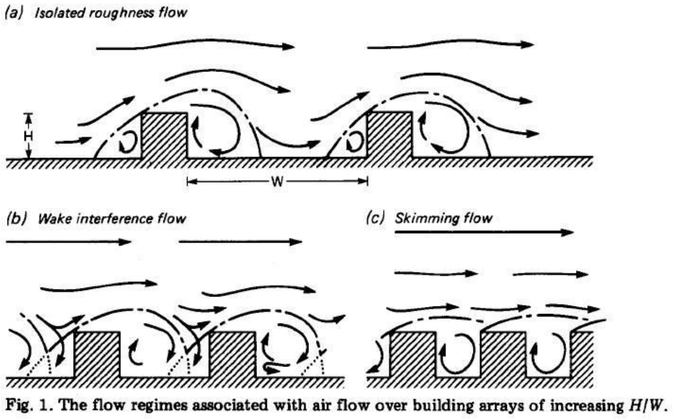


Figure 19. The flow regimes associated with wind flow over building arrays of increasing H/W. (Oke, 1988)

By having straight wide streets parallel to the prevailing wind flow the wind is channeled through the city (Ng, 2010). Ng mentions that a high density city naturally has a high aspect ratio and it is not uncommon for cities to have aspect ratios of up to 10. A solution for the perpendicular streets in high density cities is to create air paths, allowing wind to flow through gaps between the buildings. The width of the air path should be approximately half of the total width of the buildings along the street. If the buildings are very high the recommendation of width increases. For aspect ratios above 3 the width of the air path should be doubled for every integer. Another dilemma for cities with a high H/W is that it is directly correlated with a high ground coverage ratio. By increasing the ground coverage ratio from 10 % to 30 % the wind speed will decrease by half and by half again between 30 % and 60 %. Even with a high ground coverage air ventilation can be improved by having “holes” through the building façade at the ground level, known as “spatial porosity” (Ng, 2010).

Most studies that deal with the wind flow through cities have dealt with urban canyons with aspect ratios below 2 and therefore the mixing between the urban canopy layer and the roughness sub-layer for higher aspect ratios are uncertain (Nakamura & Oke, 1988).

Cities with an aspect ratio above 4 have a mediocre outlook for breeze penetration (Aynsley, 1997). Aynsley also states that when streets and buildings are not parallel to the prevailing wind flow the width of the street becomes paramount. Wide urban canyons are preferable and the L/H of the canyon should not exceed five in order to have an adequate wind penetration (Chan et al, 2001).

2.2.2 Street orientation

The city of Fortaleza faces the ocean to the north and to the east, thus making breezes from the sea an important part of the microclimate (Schiller & Evans, 1998). However most of the wind comes from the east and south-east leaving the northern shores calm. It´s important to maximize the wind flow through the city for a cooling effect. This is done e.g. by orienting the major streets parallel to the major wind flow so that the wind can be channeled along the street (Aynsley & Gulson, 1999) (Figure 20).

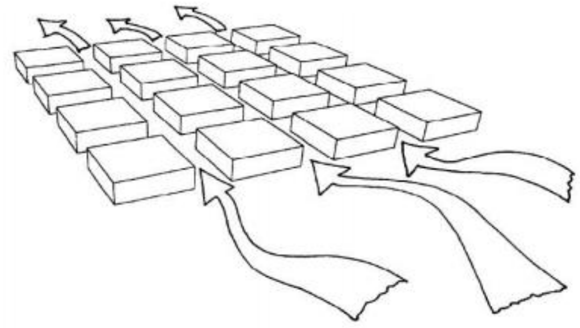


Figure 20. Straight streets parallel to the wind flow creates a channeling effect through the city (Santamouris & Papanikolaou, 1999)

By orienting the streets with an angle to the major wind flow between 10-30° the conditions for cross ventilation in the buildings along these streets are optimized which is of high importance for passive cooling (Niachou & Santamouris, 2005). If the wind hits the façade at an angle of 45-60° the wind will be deflected (Schiller & Evans, 1998). The street orientation has a higher effect in an area with high aspect ratio (Ng, 2010).

2.2.3 Urban morphology & Building design

The streets of the city should preferably form a grid pattern for maximizing wind flow throughout the city as discussed above in “street orientation”, seen in the middle of Figure 21.

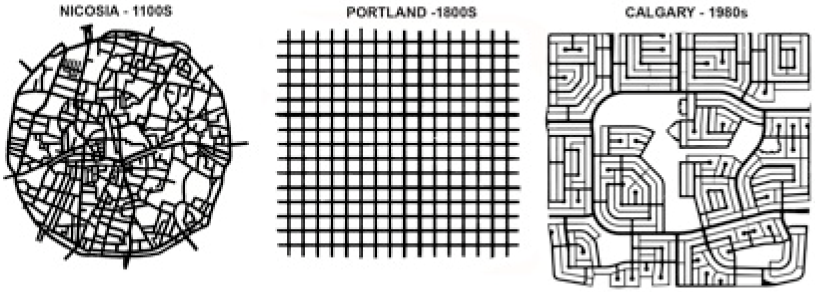


Figure 21. Street patterns of different cities, Portland has a gridiron pattern (Gramminos & Pollard, 2009).

If the city has a uniform canopy a large part of the wind will be pushed over the city with little cooling effect at street level (Aynsley & Gulson, 1999). A non-uniform urban canopy with high buildings spread out in the city will act as wind towers, deflecting airstreams at high elevations down to the air at ground level (Givoni, 1998). The height variation should be declining towards the wind flow (Ng, 2010). Givoni also states that the wind "caught" from higher elevations has a lower air temperature and higher wind speed than that of the air close to the ground thus increasing the cooling effect. This phenomenon is also known as the "downwash effect" (Ng, 2010). The towers should be tall and thin and have a space of at least 6 times their widths between each other. In order to achieve adequate wind conditions it is important to make use of the existing wind since it easily can be redirected but not easily created (Aynsley & Gulson, 1999).

A highly dense city will often have an increased urban heat island (UHI) effect (Givoni, 1998). Many studies have found a relation between a high aspect ratio and increased UHI (Ng, 2010). Research in London show that expansion of urban areas decreases the wind flow in the city (Ng, 2010).

Buildings should be elongated with the principal façade facing north and south to minimize solar radiation during early mornings and evenings (Schiller & Evans, 1998). Schiller and Evans (1998) states that the western façade often gets more sunlight than the eastern façade due to cloud protection in the east in the morning. Elongated buildings facilitates cross ventilation due to a shorter distance between high and low pressure zones (Niachou & Santamouris, 2005). Elongated buildings oriented parallel to the prevailing wind flow have smaller stagnant zones than a rectangular building of the same size (Ng, 2010).

The external color of the buildings should preferably be light to increase the albedo and thus the reflection of sunlight (Aynsley, 1997). However, pedestrians walking in areas with high-albedo might experience the resulting glare as a disturbing. Erell (2013) concludes that roofs always should have a high albedo to reduce the cooling need of buildings.

Obstructions along the shore should be avoided (Figure 22), especially buildings with the principal façade perpendicular to the prevailing wind flow (Givoni, 1998). Buildings with gaps along the waterfront are better for city air ventilation (Ng, 2010). Aerodynamic buildings along the shore can also be used to allow the onshore breeze to pass through the city (Aynsley & Gulson, 1999).

Figure 22. Aerial view of the northern shore of Fortaleza. The densely spaced buildings may act as obstructions to sea breezes (CC, 2015).

Givoni (1998) reflects that, when having to chose between shade and ventilation, ventilation may be more important in a hot humid city. In a another report Givoni states that the orientation to the prevailing wind is not as important as solar shading for buildings, perhaps these statements are not in conflict because one is reffering to the street level and the other to the building design (Aynsley, 1997).

A recent study shows that in highly dense cities, anthropogenic heat, especially emitted from vehicles, are the main contributor to the rising air temperatures at ground level (Hii, 2015). Simulations in Hii´s study show that the city morphology and density affects the flow and heat transfer in urban canyons.

2.2.4 Vegetation

Urban greenery can create an “oasis effect” and mitigate urban warming at both a small and a large scale (Ng, 2010). Tall trees can function as “solar umbrellas” and provide shading for outdoor spaces if the tree trunk is leafless and they have a dense crown (Schiller & Evans, 1998). Trees can be placed along pathways to protect pedestrians and to decrease the mean radiant temperature (Schiller & Evans, 1998). Small trees and bushes inhibit wind flow at pedestrian level and do not provide efficient shade (Schiller & Evans, 1998). Grass areas pose least friction to wind flow and allow for best possible ventilation (Givoni, Impact of planted areas on urban environmental quality: A review, 1991). Grass may lower the air temperature by evaporative cooling similar to other vegetation but on a mesoscale and not locally (Heilman & Gesch, 1991). Grass reflects aproximatley 20 % of the incoming sunlight compared to asphalt which only reflects about 10 %. Concrete or other light materials reflect a larger part of the sunlight which means that more sunlight is reflected on pedesterians (Erell et al, 2011). Even though the albedo for both grass and asphalt is relatively low, the surface temperature of grass is lower than dry surfaces due to evapotranspiration (Erell et al, 2011).

Trees have been proven to lower air temperatures in cities, but the underlying reasons are debated. The cooling effect from evapotranspiration have been questioned since the process of photosynthesis will occur only at direct sunlight on leafs at the top of tree canopy. For this reason it is thought that the resulting cooling effect mainly originates from surface shading (Erell et al, 2011). A study conducted in Singapore showed that buildings along a street surrounded by a large amount of dense trees can save up too 20% of energy needed for cooling on a clear day and almost 40% on a cloudy day (Ng, 2010). However, the experiment showed that energy savings were almost zero when situated close to a heavily trafficated street during day time. Too many trees along a busy trafficated street may cause pollution problems since the mixing of air between the different air layers is inhibited: RSL and UCL (Schiller & Evans, 1998).

The UHI effect is largest at night and is countered by having large open areas for nocturnal cooling e.g. parks (Ng, 2010). The kind of vegetation in the park will have a large impact on its cooling effect (Erell et al, 2011). Parks need to have a large area to have a significant cooling effect of the city (Erell et al, 2011) and a substantial amount of energy can be saved by having buildings located close to a large park (Ng, 2010). Placing vegetation strategically can lower the surface temperature on roofs and façades at a microclimatic scale. Extensive use of vegetation in a city can mitigate the UHI effect (Ng, 2010). Ng also points out that rooftop gardens can lower the cooling load for buildings. It has been shown that on hot sunny days the average temperature of walls shaded by trees or by a combination of trees and shrubs could be reduced by 13.5-15.5 °C (Parker, 1983). Parker concludes that with strategically placed trees the energy reduction of buildings can be reduced by 30-50%. Parker's research stands in agreement with Amory Lovins conclusion that Los Angeles, with simple microclimatic solutions such as light colored roofs and paving and trees for shade, could lower the average air temperature by 2.8 °C and reduce the space cooling load by 20% (Lovins, 2011).

2.2.5 Storm water management

Storm water management is an important aspect in city planning. In hot-humid regions, such as Fortaleza, the main objective is usually to protect urban areas from floods by a rapid disposal of the excess storm water (Givoni, 1998). Givoni further states that storm water management can be used e.g. to prevent polluted water from reaching nearby waterbodies, protect against floods or even to passively cool buildings. In order to prevent the polluted water from reaching nearby waterbodies the water can be stored in ponds or temporary floodplains where it can infiltrate the ground and evaporate. Flat rooftops can store a certain level of water which can decrease the cooling load of a building when the water evaporates. Other possibilities can be to allow certain areas of the street and parking lots to flood to a degree as long as the usability of the area is not obstructed (Givoni, 1998).

Using floodplains as temporary storm water storage can be an effective way of preventing storm water from reaching nearby water bodies and to control floods in urban areas. Floodplains has for example been incorporated to a large extent in the city of Curitiba in southern Brazil (I2UD, 2004).

Storm water in urban areas may contain pollutants such as sediment, heavy metals, pesticides and nutrients (McCarthy, 2008). When the water has evaporated and infiltrated the ground the pollutants are stored in the soil and may also be transported into the groundwater. Depending on the location and the amount of pollutants in the area the storm water may have to be treated before reaching recreational areas. But treatment of the storm water does not necessarily mean that all of the water has to be cleaned. The "first flush"-effect is phenomenon which means that the amount of pollutants is usually a lot higher in the first volume of storm water runoff (McCarthy, 2008). Having an additional system that treats the first flush could help in minimizing the spread of pollutants to green recreational areas and nearby water bodies.

2.2.5.1 Calculating storm water runoff

Storm water runoff is often calculated in volume per unit time in order to be able to dimension drain pipes, ponds or channel flow to be able to handle the peak flow of a certain rainfall. This can be done by using the rational method where the flow in volume per unit time is found by multiplying the catchment area with the rainfall intensity and a runoff coefficient (Bengtson, 2011).

$$Q = c * i * A$$

Where,

$Q = Peak\ discharge\ (m3/s)$
$c = Rational\ method\ runoff\ coefficient$
$i = Rainfall\ intensity\ (mm/hour)$
$A = Catchment\ area\ (m2)$

The runoff coefficient, c, is the fraction of water landing on an area that becomes runoff and is dependent on the urban material (Bengtson, 2011). The coefficient value for e.g. asphalt and rooftops is approximately between 0.7 and 0.95 (LMNO Engineering, 2015). No calculations of peak discharge were made in this project due to that there were no information to be found on rainfall duration.

2.2.5.2 Intensity Duration Frequency curve

Storm water management systems are often dimensioned to handle a certain design rainfall event which can be found by using an Intensity Duration Frequency curve, or IDF curve (FlowWorks, 2009) (Figure 23). The IDF curve describes how often a rainfall with a certain intensity and duration will occur and can be used e.g. to identify a 1-year, 5-year or a 10-year rainfall. Rainfall duration is also required to construct an IDF curve and thus was not created in this project.

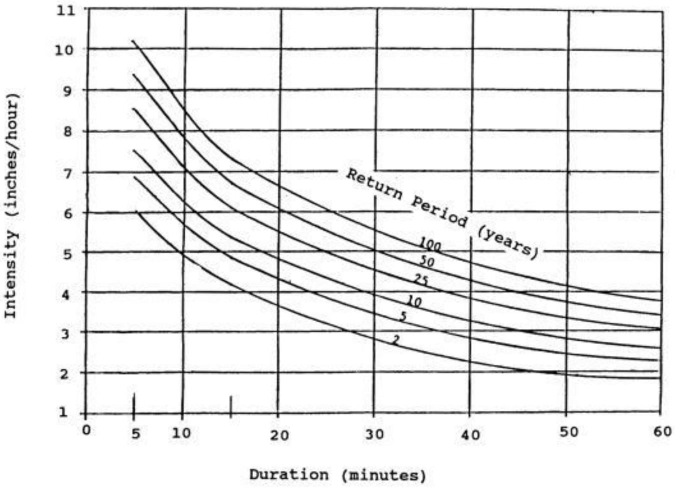


Figure 23. IDF curve showing a statistic return period of rainfalls in Birmhingham (Pitt, 2002)

3 Method

3.1 Simulation tools

ENVI-MET 3.1 is a climate simulation software which includes climate change adaption, human comfort and health (ENVI-MET, 2015) and was used for the climate simulations in this study. There are other climate simulators, such as Ecotect, but ENVI-MET is a comprehensive simulator which can simulate a large amount of climatic factors simultaneously. ENVI-MET can also calculate thermal comfort in PMV and is a freeware. ENVI-MET is a common tool to use in microclimatic research.

SketchUp is a 3D modeling software (SketchUp, 2015) and was used to get a visualization of the models used in the study. The software was also used to generate measurements of street and building dimensions.

Ecotect is a sustainable building design software which can conduct simple solar, shading and wind simulations (AUTODESK, 2015).The shade simulations were conducted in Ecotect by importing a ".3ds" file from SketchUp of the 39 m high buildings and by using weather data from Pinto Martin, an airport located about 7 km from the coast south of the central business district.

3.2 Construction of Model 1

The area chosen as a reference in this project is a part of the central business district called Meireles. It is representative of the more crowded and densely populated areas in Fortaleza. Once the area to be investigated was chosen it was modelled in SketchUp (Figure 24). Google Earth was used to get the model to scale and to get the correct orientation. The model was also created to get a good visual picture of the area, and to be able to get measurements of building and street dimensions in the area.

Some limitations and simplifications of model design and input data was implemented to limit the amount of simulations needed to be conducted. Two models are used in this project; the first model (Model 1) is the reconstruction of the chosen area in Fortaleza and the second model (Model 2) is a test area in which the different types of urban design elements (aspect ratio, street orientation and vegetation) was simulated.

Figure 24. SketchUp model of the chosen area in Meireles, Fortaleza.

The model of the chosen area in Fortaleza, Model 1, was constructed in ENVI-MET as seen in Figure 25. In ENVI-MET, buildings and streets are drawn in cells of chosen dimensions. When choosing the dimension of the cell, a compromise had to be made between the precision of the model, the maximum amount of cells in ENVI-MET and simulation time. Small dimensions of the cells means higher precision but a longer simulation time. ENVI-MET provides the option (when simulating) to choose from 100x100x30 (x, y, z), 180x180x30 and 250x250x250. In order to get the best possible resolution and at the same time be able to get an adequate design where house and street dimensions were as similar to reality as possible, a cell size of 5x5m was chosen. The area is 550x315m, thus 180x180x30 had to be used to fit the model. Building lengths and widths was measured in the SketchUp model (Figure 24). Building height was determined by using 3m as a standard height of one floor thus multiplying 3 by the amount of floors in respective building. The width and length of the buildings was approximated as close to reality as possible with the limitation of drawing in 5x5m cells.

The green areas in Figure 25 represent different kinds of trees that was considered to have any effect on the microclimate in the city. These were trees with a large or dense canopy that provided shade for the street and could possibly obstruct the wind flow. The trees that were not taken in to account were small, had little or no crown layer and provided neither shade nor had any apparent effect on the wind flow. The trees that was considered to have any effect on the microclimate in the city was entered into ENVI-MET according to the programs´ standard list of trees. The ground cover in the area consisted mostly of asphalt and concrete. The ground cover in the model was chosen to be asphalt since asphalt covered the majority of the area.

The calibration point, the red dot in the middle of the model, is the point where data from the simulations (air temperature and relative humidity) was taken and used to calibrate the model (see 3.4 for further explanation). The location of the calibration point was chosen as it is placed right between two adjacent high-rise buildings which provide shade most of the day.

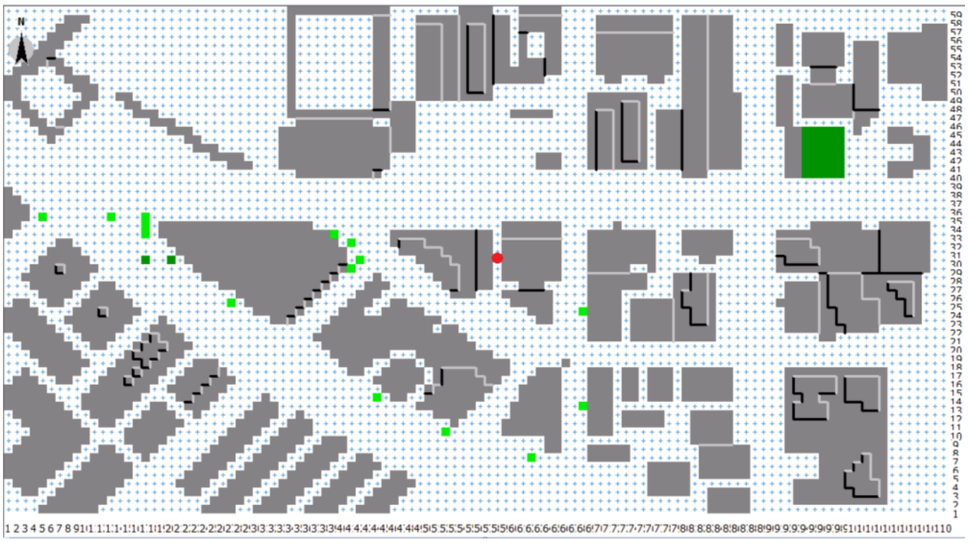


Figure 25. Model 1 constructed in ENVI-MET with buildings (grey), trees (green) and the calibration point (red).

3.3 Selected design of the new area, Model 2

3.3.1 Building dimensions of Model 2

Model 2 was constructed with a simple house design and based on two important criteria when considering the resulting microclimate. The first criteria was to have long façades facing north and south which resulted in elongated blocks in an east-west direction. The second criteria was to provide uninterrupted wind flow through the urban area, thus designing a grid with straight streets.

The dimensions of the buildings and the street width was determined to be similar in shape of the buildings in Model 1, see Figure 26. A street width of 25m was selected since the street width of the two main streets in Model 1 are approximately 25m. The block length in Model 1 is approximately 90-100m thus choosing a block length of 90m in Model 2. The building width of 20m was chosen as an estimation of the average building width in Model 1 which varied between 15m and 25m. Up to an aspect ratio of 3, and when L/W does not exceed 10, the air path width divided by the total width of the two adjacent building blocks ($W/2W_b$) should preferably not be below a value of 0.5. With the dimensions in model 2, L/W equals 3.6 and $W/2W_b$ equals 0.625.

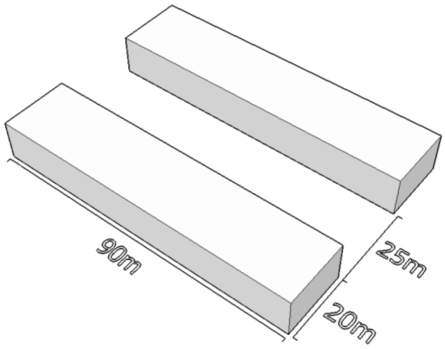


Figure 26. Building dimensions of Model 2. The height varies in the simulations.

3.3.2 Aspect ratio

The range of values of the aspect ratio to be simulated was determined based on the requirement to optimize wind flow since wind is one of the most important factors when it comes to thermal comfort in urban areas (Givoni, 1998). The largest wind flow for parallel streets in urban canyons is reached between an aspect ratio value of 0.4 to 1.5 (Wong, 2005). In this project the aspect ratio is simulated between a value of 0.48 (Figure 27) and 2.16 (Figure 28) (12m and 54m respectively). The aspect ratio was simulated up to 2.16 to see how the wind speed in ENVI-MET was affected above an aspect ratio of 1.5.

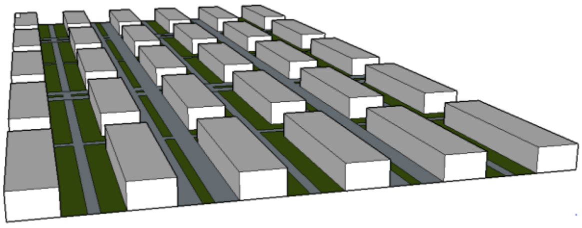


Figure 27. Model 2 with 12m high buildings and an aspect ratio of 0.48.

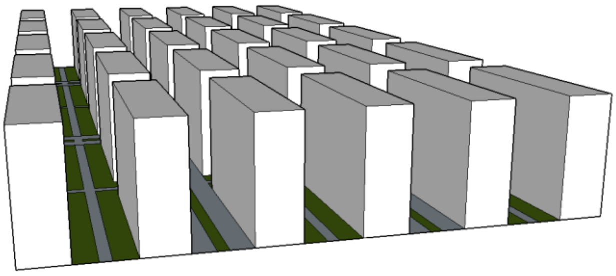


Figure 28. Model 2 with 54m high buildings and an aspect ratio of 2.16.

3.3.3 Street orientation

Model 2 was simulated for two different street orientations, an east-west direction (Figure 29) in the first simulation and a 30 degree tilt to the south in the second (Figure 30). The east-west direction was simulated because the main streets are parallel to the wind flow which should provide optimal conditions for wind penetration. The 30-degree tilt may reduce wind velocities in the area but can provide natural cross-ventilation to the buildings. When choosing between a 30-degree tilt to the north and a 30-degree tilt to the south, the tilt to the south was selected. The tilt to the south is a better choice considering the second major wind direction which comes from the south east. A tilt to the north would mean that the south-western wind will have an angle of incidence of 75 degrees towards the main streets and buildings, but only 15 degrees for the tilt to the south.

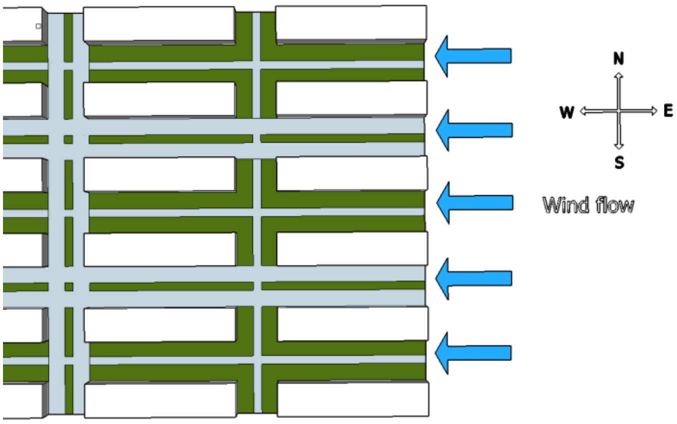


Figure 29. Model 2 with the main streets in an east-west direction with the main streets parallel to the wind flow.

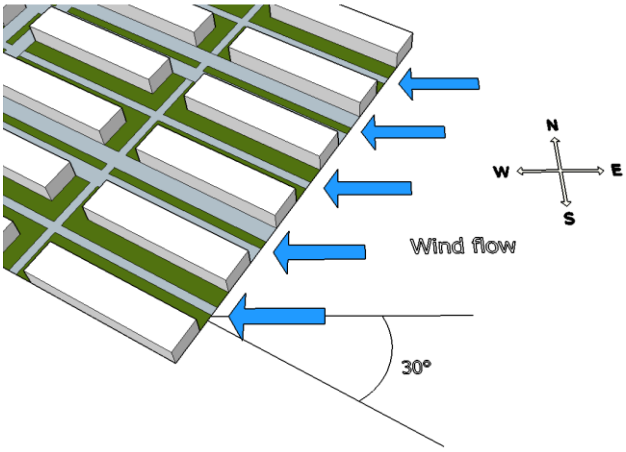


Figure 30. Model 2 with main streets tilted 30 degrees to the south.

3.3.4 Model 2 in ENVI-MET

Model 2, (Figure 31) was constructed with a street width of 25m and house dimensions of 90x20m. The area size is 550x245m. Ground cover was chosen to asphalt.

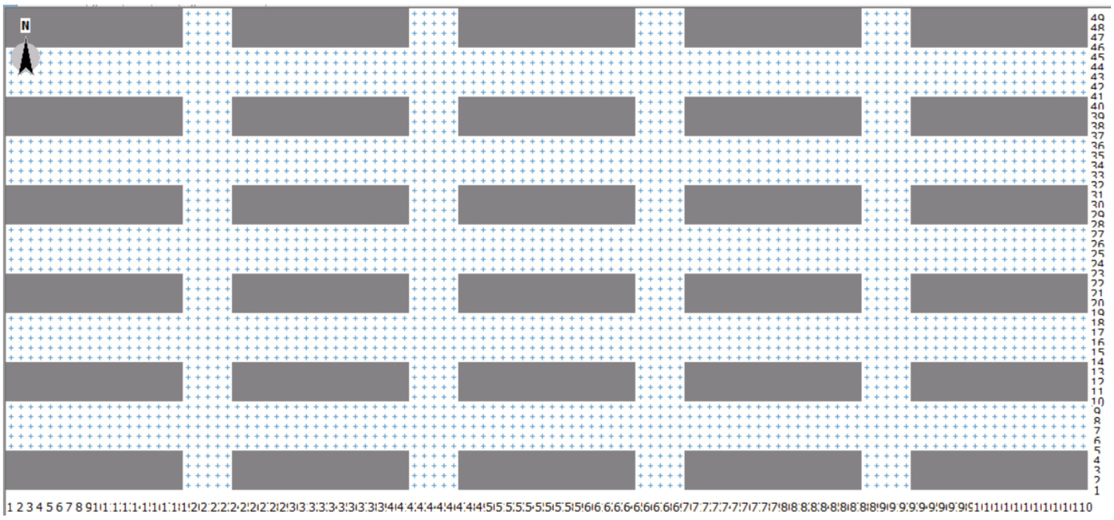


Figure 31. Model 2 constructed in ENVI-MET.

3.3.5 Vegetation

Two types of vegetation cover in Model 2 was tested and simulated in ENVI-MET and compared to the same model without vegetation. The first simulation consisted of partial grass cover and the second with both grass and trees. The grass cover was placed as seen in Figure 32. The trees that were used in the simulations were 15m high, very dense trees with a leafless base for the purpose of providing shade and to cause as little wind obstruction as possible on ground level. Trees were placed as alleys along the streets and walking paths as seen in Figure 33.

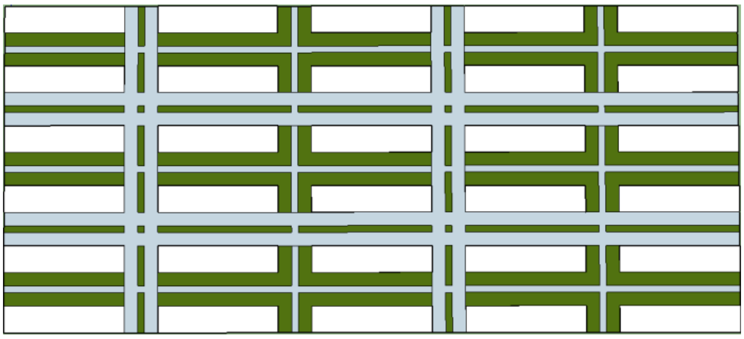


Figure 32. Model 2 with partial grass cover (green) next to the streets and walking paths (grey). Builings blocks are depicted in white.

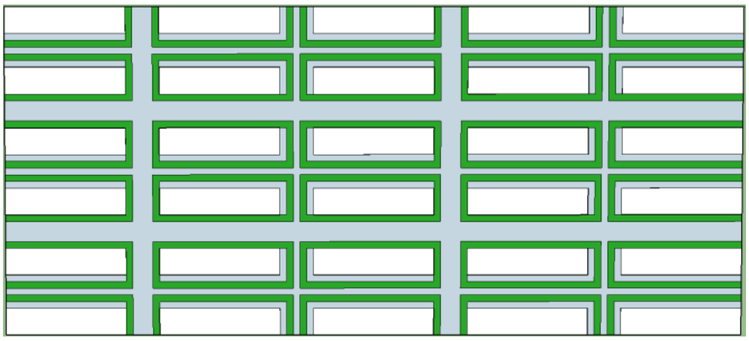


Figure 33. Model 2 with trees (green).

3.3.6 Thermal comfort index

The thermal comfort index used in this project is Predicted Mean Vote, PMV, since it can be calculated automatically in ENVI-MET. PMV is designed for indoor conditions and may provide inaccurate values of outdoor thermal comfort. However, the PMV values received from the different simulations will be compared to each other, providing information of how the thermal comfort conditions may have changed and conclusions of improvement or deterioration of the thermal comfort can be made.

3.4 Microclimate simulations

When simulating in ENVI-MET, climatic data from Fortaleza was used together with input data that had to be calibrated (7.1 in appendix). The input data had to be calibrated so that when simulating Model 1, the values of air temperature and relative humidity extracted from the “calibration point” (Figure 25), would show similar results as the climatic data of December for Fortaleza taken from the Federal University of Ceará. The input data to be calibrated was Cloud composition and factor of shortwave adjustment, specific humidity in 2500 m and the initial air temperature.

3.4.1 Wind direction and speed

When determining an input wind direction the wind data for Fortaleza provided the information that there were two major wind directions, east and south east, (see Figure 10) and little or no wind from the other directions. While the south eastern wind is common, the eastern wind was selected since it would have an effect during a larger part of the year. The south eastern wind direction is also close to the dominant wind direction.

In order to get the optimal wind penetration into the area the main streets should be parallel to the wind direction (Ng, 2010) thus an eastern wind was selected as the standard input wind direction in Model 2.
The input wind speed for Model 1 and Model 2 was determined by calculating the average speed for the eastern wind by adding all flows from the east and multiplying them with their respective percentage of occurrence (7.3 in appendix). The wind data was taken from Federal University of Ceará which is located 5 km from the coast. It is possible that the wind from the ocean is stronger than what is measured at this location. This was not considered in the report.

3.4.2 Calibrating the model

3.4.2.1 Cloud composition and factor of shortwave adjustment

The cloud fraction composition and the factor of shortwave adjustment was determined first.

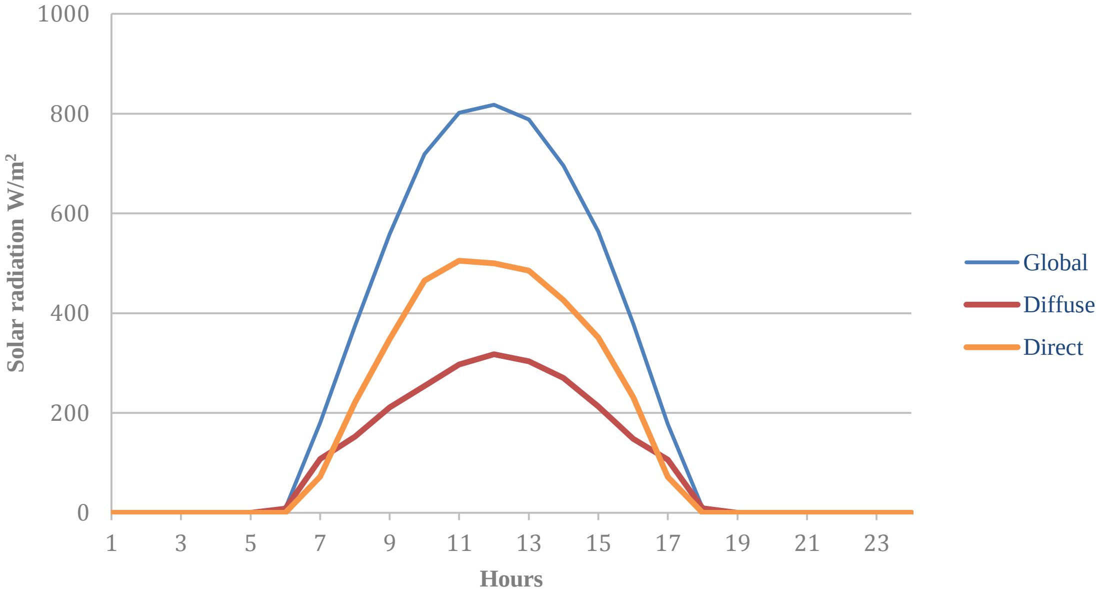
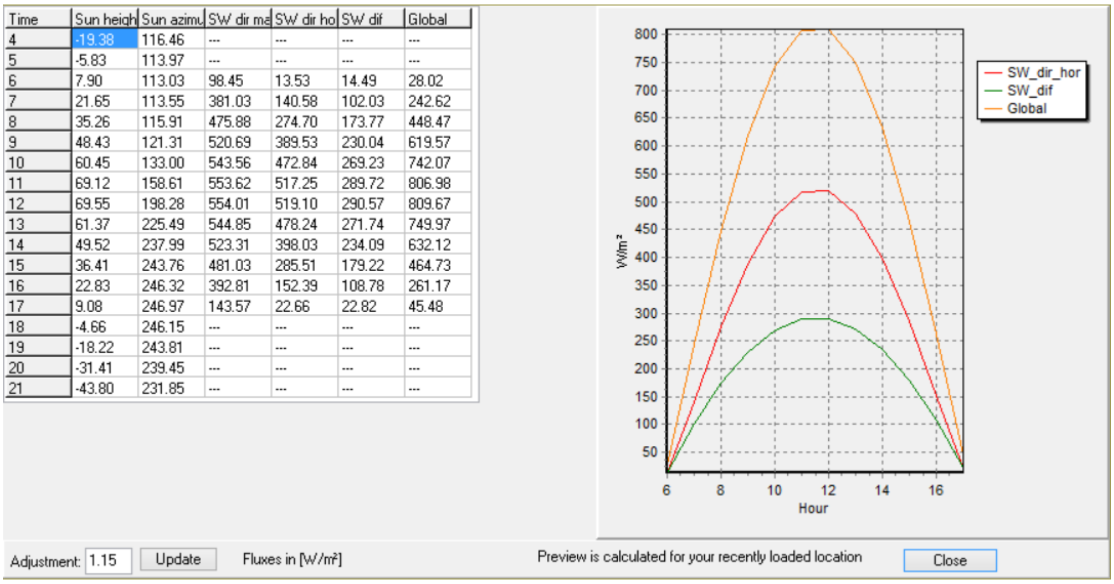


Figure 34. Hourly solar radiation data of Fortaleza during a day in December (Meteotest, 2009).

An adjustment factor of 1.15 and cloud composition of 4 on low clouds and 0 on medium and high clouds respectively provided a solar radiation that was consistent with the solar radiation conditions in Fortaleza (Figure 34). The resulting graph (Figure 35) was considered sufficiently accurate to be used in further simulations.



Time	Sun heigh	Sun azimu	SW dir ma	SW dir ho	SW dif	Global
4	-19.38	116.46	---	---	---	---
5	-5.83	113.97	---	---	---	---
6	7.90	113.03	98.45	13.53	14.49	28.02
7	21.65	113.55	381.03	140.58	102.03	242.62
8	35.26	115.91	475.88	274.70	173.77	448.47
9	48.43	121.31	520.69	389.53	230.04	619.57
10	60.45	133.00	543.56	472.84	269.23	742.07
11	69.12	158.61	553.62	517.25	289.72	806.98
12	69.55	198.28	554.01	519.10	290.57	809.67
13	61.37	225.49	544.85	478.24	271.74	749.97
14	49.52	237.99	523.31	398.03	234.09	632.12
15	36.41	243.76	481.03	285.51	179.22	464.73
16	22.83	246.32	392.81	152.39	108.78	261.17
17	9.08	246.97	143.57	22.66	22.82	45.48
18	-4.66	246.15	---	---	---	---
19	-18.22	243.81	---	---	---	---
20	-31.41	239.45	---	---	---	---
21	-43.80	231.85	---	---	---	---

Adjustment: 1.15

Fluxes in [W/m²]

Preview is calculated for your recently loaded location

Figure 35. Input solar radiation in ENVI-MET with adjusted cloud factor and solar adjustment factor.

3.4.2.2 Specific Humidity in 2500m and RH-value

The second parameter to be calibrated was specific humidity in 2500m. The RH-value was set to 70% and 19g Water/kg air on the Specific Humidity in 2500 m setting resulted in a relative humidity on ground level in Model 1 of about 70% which matched the climatic data.

3.4.2.3 Initial Air Temperature Atmosphere

The third and last parameter to be calibrated was the initial air temperature. The initial air temperature is the temperature at the hour when the simulations are starting, which is 6.00 a.m. Since ENVI-MET´s day temperature curve usually do not fit the real day temperature curve, the initial air temperature has to be calibrated to a value that likely is different to the actual air temperatur**e** at 6.00 am so that the air temperature at 14.00 matches the climatic data. By trial and error the initial air temperature was found to be 300K.

3.4.3 Simulation cases

3.4.3.1 Aspect ratio

Simulations were carried out to find the optimal aspect ratio for our area. The aspect ratio was simulated by increasing the building height by steps of 6 m in ENVI-MET from 12 m (H/W=0.48) to 54 m (H/W=2.16).

3.4.3.2 Street orientation

The orientation of the main streets was simulated for an east-western direction and a direction of 30 degrees south from the original west-east direction (formulation?) by changing the wind direction from 90 degrees (eastern wind) to 60 degrees.

3.4.3.3 Vegetation

Vegetation was simulated in two steps; the first with partial grass cover and the second with both grass and trees. Grass, ‘loamy soil’ in ENVI-MET, was simulated once in the east-western direction and the combination of grass and trees was simulated in the east-western direction and with a 30 degree tilt to the south.

3.5 Climate measurements

Climate measurements of air temperature and relative humidity were made in Meireles using TinyTags. The TinyTag TGP-4500 measure relative humidity and air temperature between 0-100% and -25°C-85°C respectively (Gemini, 2015). The TinyTag logs data at specific intervals and was set to measure at an hourly sampling interval. The accuracy of the RH measurements are ± 3% at 25 °C. The temperature is accurate to ± 0.4 °C at 25 °C.

A calibration of the TinyTags were done for validation of the measurements, described in detail below. The measurements were initially intended to be used for the calibration of ENVI-MET simulations. However, the most interesting month to analyze the thermal comfort is December, because it is the hottest month, and the TinyTag measurements were carried out during March and April, the time when the study took place. The measurements are discussed because the data highlights the difference between the indoor climate of a typical apartment and the outdoor climate in Meireles.

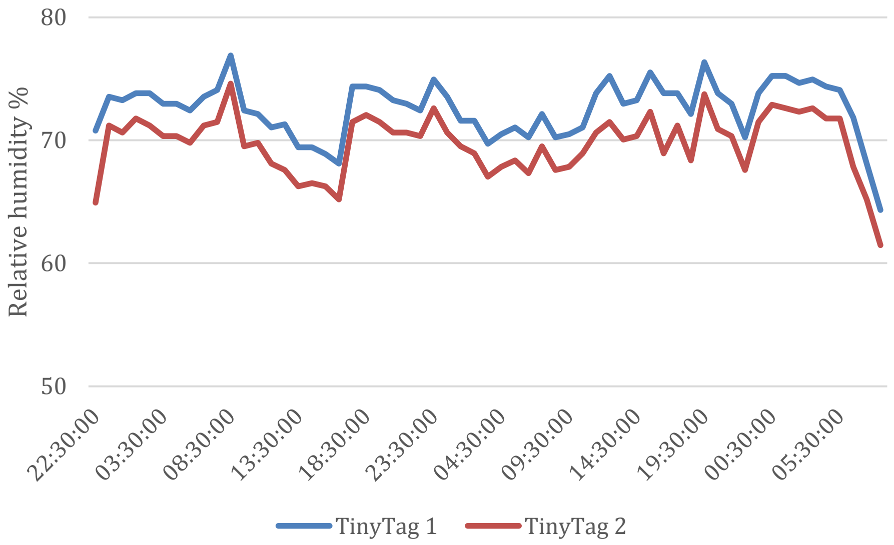


Figure 36 Comparison measurements of relative humidity by the two TinyTags during the 18th-21st of February 2015.

The TinyTags were activated on the same time, marked with a number 1 and 2. They were put on the same location, on a shelf indoors. Measurements were commenced 22.30 18-02-2015 and finished 08.30 21-02-2015. The software program EasyView was used to collect the data from the TinyTags. The diagrams present the two TinyTag measurements of relative humidity (Figure 36) and temperature (Figure 37). TinyTag 2 follows the same trend as TinyTag 1 but seem to measure the relative humidity at approximately 2 percentage units lower than TinyTag 1, see Figure 36. TinyTag 1 and 2 show similar air temperature measurements, see Figure 37. After the calibration TinyTag 1 was used for the outdoor measurements and TinyTag 2 for the indoor measurements. TinyTag 1 was equipped with an external solar shade protection and placed in a shaded place at approximately 2 m height. TinyTag 2 was placed indoors at the 5th floor in a room without AC.

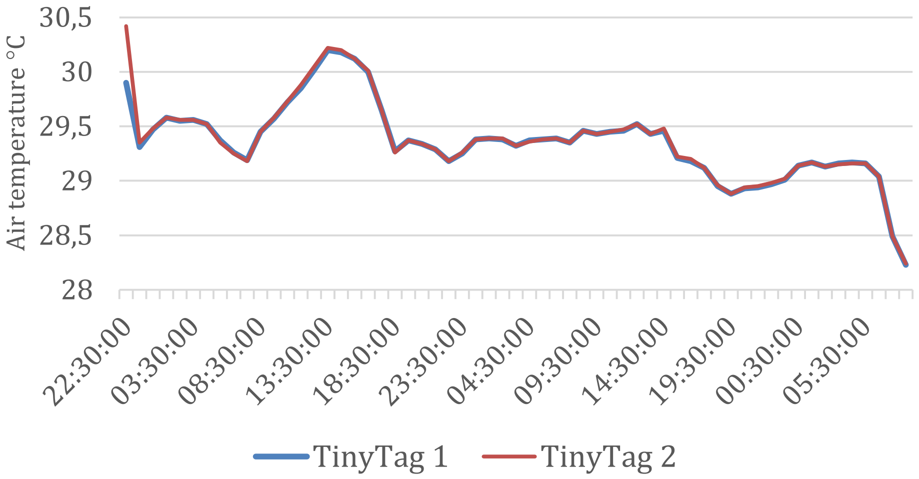


Figure 37 Calibration measurements of the air temperature by the two TinyTags during the 18th-21st of February 2015

3.6 Cooling degree days

The cooling degree days (CDD) were generated from BizEE (2015) (7.4 in appendix). The sample size used to calculate the degree days was three years, 2012-2015. It's also worth noting that the base temperature was set as a set number, however, it is likely that the comfort temperature will vary throughout the year following the seasonal variations, even though the temperature variations are quite small in Fortaleza.

The base temperature was roughly estimated to 26°C since the literature indicates that the thermal comfort range is approximately between 26°C and 30°C (Yang et al, 2012). An appropriate calculation of the base temperature requires information of the energy usage of the building and a regression analysis.

3.7 Storm water management

3.7.1 Mapping the catchment area

The catchment area was mapped by investigating the area during rain, drawing the direction of the flowing water on a map. The map was created in Google SketchUp and lines were drawn between the points where water was flowing in two separate directions. The size of the catchment area was calculated in Google SketchUp.

3.7.2 Finding the 10 year rainfall

Precipitation data for Fortaleza from 1980 to 2014 was used with data missing for the years 1983, 1990, 1996, 1997, 2000 and 2001. Thus data from a total of 29 years was used.

The 10-year rainfall was calculated by identifying the three largest rainfalls and calculating the average value.

3.7.3 Runoff volume and floodplain depth

Because of the fact that the catchment area had no (or at least few and small) infiltration surfaces, it was assumed that all storm water becomes runoff. The runoff volume was estimated by multiplying the 10 year rainfall with the catchment area. The runoff volume from the area of Model 2 alone was also calculated to find out how much water would have to be retained if Model 2 only would have to deal with its own storm water.

The required floodplain depth of the green vegetated areas in Model 2 was calculated by dividing the runoff volume with the vegetated area.

A realistic average depth was assumed to be somewhere below 0.8 m so that the 5 m wide grass areas, located in the middle of the highways, will not have too steep slopes.

3.7.4 Limitations, Storm water management

All storm water is assumed to become runoff, no regard is taken to retention of water in cavities, in the urban material or through interception by trees.

No calculations of water transport over time will be made. Only the possibilities of storing the total runoff volume of a 10 year rainfall will be discussed in this project.

The 10-year rain fall is found by using data that presents the amount of water precipitated during one full day, thus it could be based on several rain falls occurring on the same day.

4 Results

4.1 Microclimate simulations in ENVI-MET

The results from the microclimatic simulations for Model 2 for aspect ratio, vegetation and street orientations are presented in 4.11, 4.1.2 and 4.1.3. The results from Model 1 are presented in 4.1.4. All data from ENVI-MET is extracted at a height of 2 m.

4.1.1 Aspect ratio

The average values of wind, air temperature and mean radiant temperature for the different aspect ratio simulations for main streets parallel to the wind flow was calculated in ENVI-MET Extract and plotted in separate graphs (Figure 38, Figure 39 and Figure 40).

The wind speed (Figure 38) was found to increase slightly from about 2.25m/s when H/W equals 0,48 to 2.5m/s at H/W=0.95. The wind speed increased to about 2.8m/s between H/W=0.95 and 1.2 and then decreased to 2.4m/s at a H/W value of about 1.45 and with a slower linear reduction from H/W=1.45 and onwards.

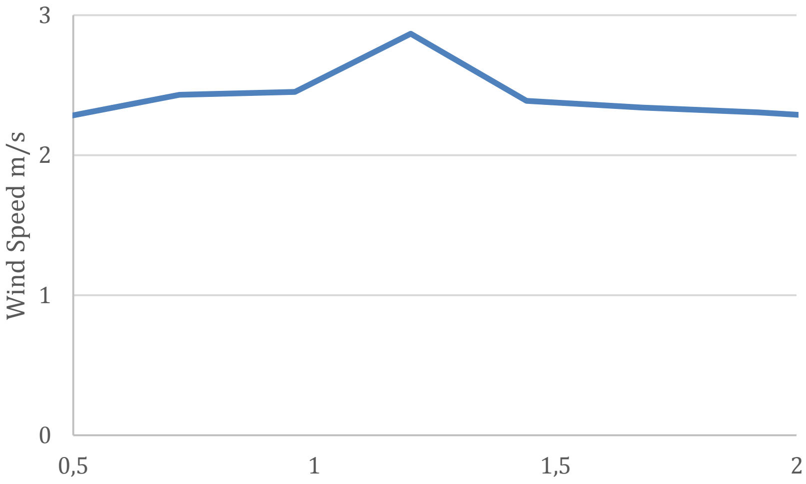


Figure 38 Wind speed at 14:00 for the different aspect ratios

The air temperature decreased linearly with increased H/W value (Figure 39). The air temperature was found to be about 31.9 °C with H/W=0.48 and about 29.7 °C with H/W=1.68.

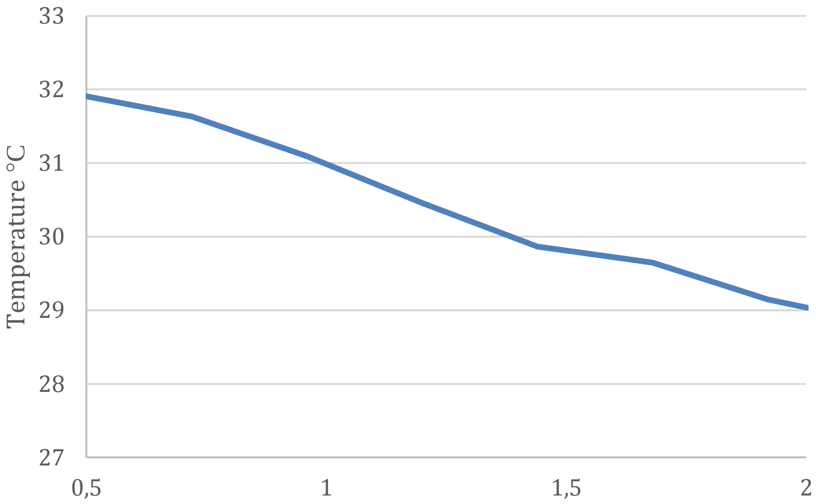


Figure 39 The air temperature at 14:00 for the different aspect ratios

The mean radiant temperature showed a linear decrease (Figure 40) with increased H/W value from about 58 °C at H/W=1.46 to 47 °C at H/W=1.56.

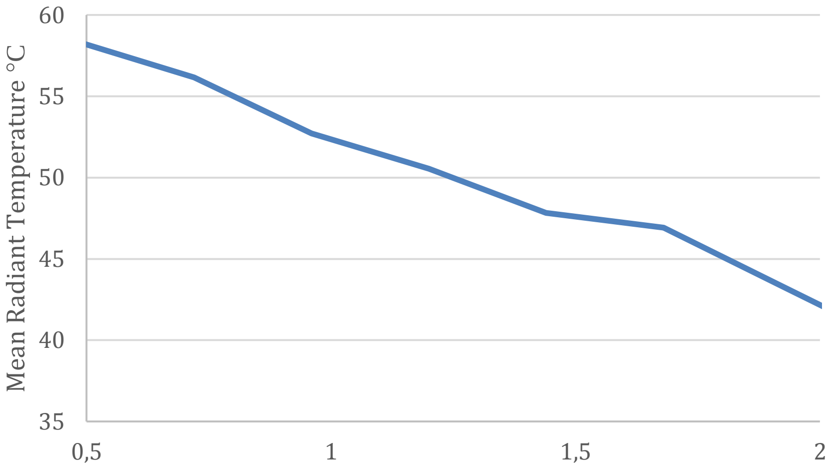


Figure 40 Mean radiant temperature at 14:00 for the different aspect ratios

4.1.2 Street orientation

Two different orientations of the street were simulated: one parallel to the wind flow, “0 degrees”, and the second one 30 degrees tilt to the south of the major wind flow “30 degrees”. The air temperature and mean radiant temperature does not differ much from the two simulations. The wind speed in the 0 degree scenario has a higher wind speed of 2.4 m/s compared to the 2.1 m/s wind speed observed in the 30 degrees scenario (Table 1). The MRT distribution for the streets parallel to the wind and the wind distribution for the two street orientations are pictured in Figure 41, Figure 42 and Figure 43.

Table 1. Simulations at 14:00 for street oriented "0 degrees" and "30 degrees" south of the prevailing wind flow

Simulation	**Wind m/s**	**Temp °C**	**MRT °C**	**RH %**	**PMV**
0 degrees Celsius	2,4	31,7	47,0	63,1	3,3
30 degrees Celsius	2,1	31,3	45,7	64,6	3,3

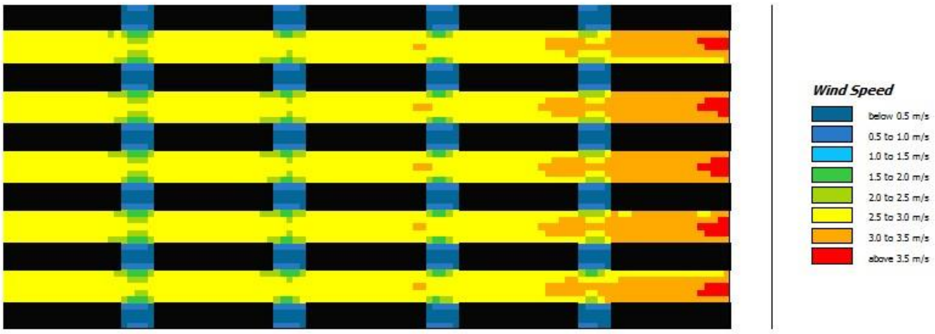


Figure 41 Wind speed simulation at 14:00. Main streets parallel to the wind direction and without vegetation

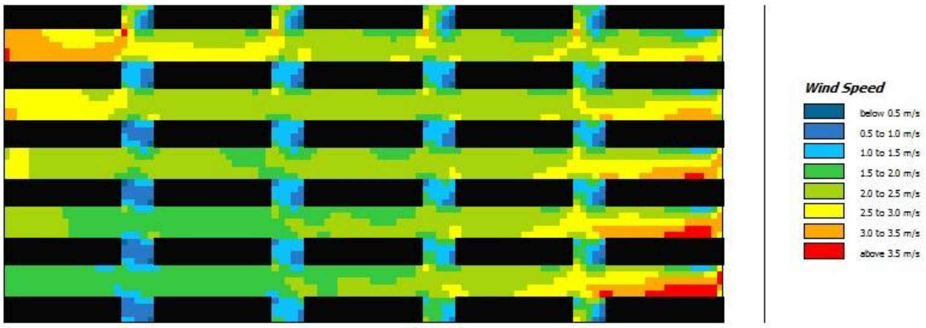


Figure 42 Wind speed simulation at 14:00 for main streets oriented 120° from N

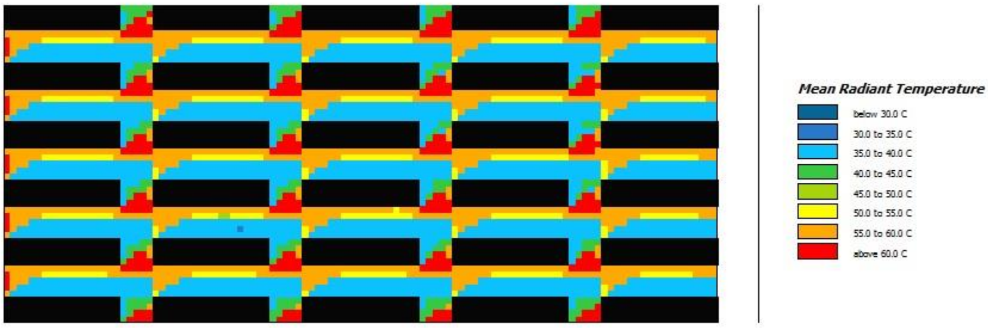


Figure 43. MRT simulation at 14:00 for main streets parallel to the wind direction

4.1.3 Vegetation

Two different simulations were done do test the effects of vegetation by comparing them to the base scenario of 39 m high buildings and no vegetation. The results are summarized in Table 2. Some of the simulation results can be viewed in more detail in Figure 47, Figure 48 and Figure *49*.

Table 2 Data from the simulations at 14:00 with "No vegetation", "Grass", "Grass and trees", the values are averaged from the whole simulation area excluding the buildings.

Simulation	**Wind m/s**	**Temp °C**	**MRT °C**	**RH %**	**PMV**
No vegetation	2,4	31,7	47,0	63,1	3,3
Grass	3.1	30.9	44.0	67.3	2.9
Grass and trees	1.6	29.7	37.1	75.9	2.4
30° Grass and trees	1.6	29.7	36.9	75.9	2.4

The "Grass" and Grass and trees" simulations shows the lowest average wind speed of 1.8 m/s followed by the no vegetation scenario with an average wind speed 2.4 m/s. The highest average wind speed was observed at the simulation with grass at 2.8 m/s, shown in Figure 44 below.

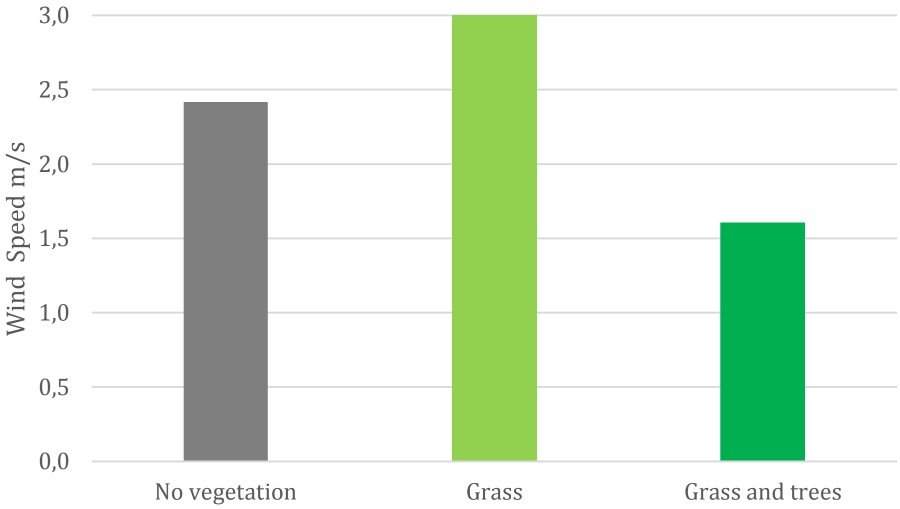


Figure 44. The wind speed at 14:00 for "No vegetation", "Grass", "Grass and trees" with 39m high buildings.

The basic simulation "no vegetation" has an average MRT of 47.0 degrees compared to a slightly lower MRT for the Grass simulation of 43.7 degrees. The "Grass and tree" simulation shows a significant lower MRT of 37 degrees probably due to the shade effect of the trees as seen in Figure 45 below.

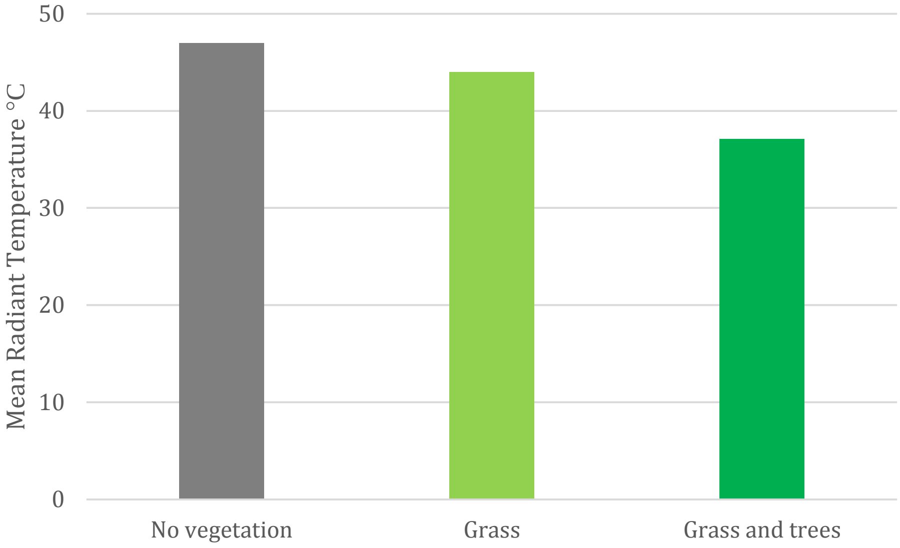


Figure 45 The Mean Radiant Temperature at 14:00 for "No vegetation", "Grass", "Grass and trees"

Vegetation increases humidity in the area. The "Grass and trees" simulation shows a humidity of 76.2%, The "Grass" simulation has approximately 67.9% compared to the basic scenario "No vegetation" at 63.1% (Figure 46).

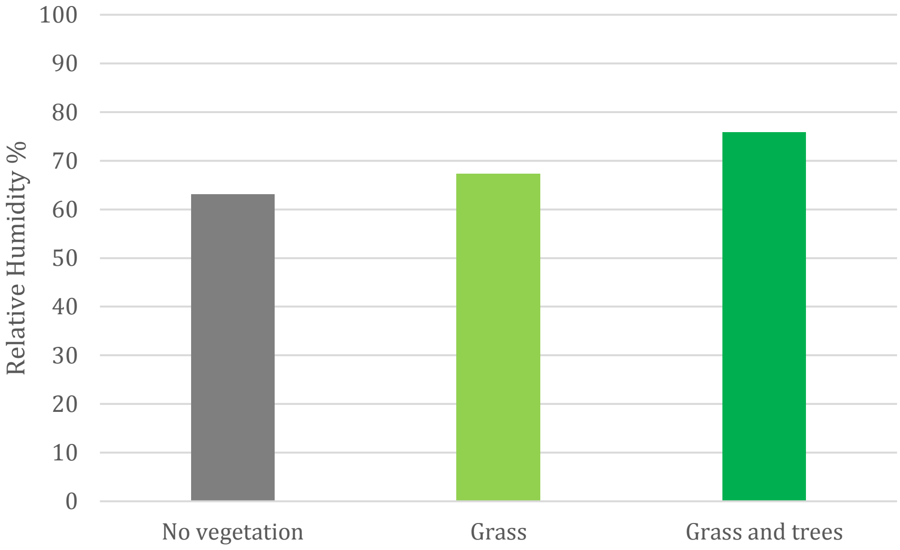


Figure 46 Relative Humidity at 14:00 for "No vegetation", "Grass", "Grass and trees".

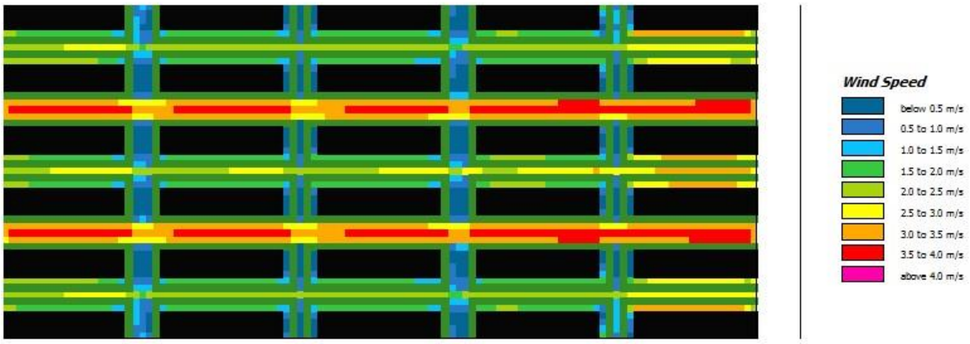


Figure 47 Wind speed simulation at 14:00 Main streets oriented 90° from N (=E-W) with grass and trees

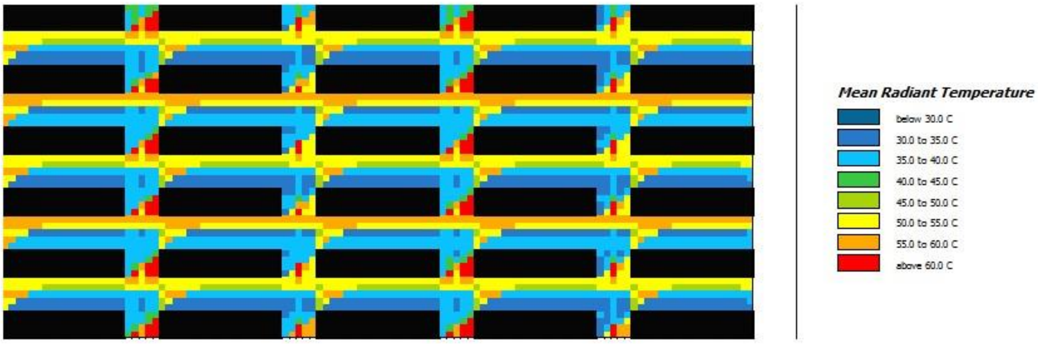


Figure 48. MRT simulation at 14:00 for main streets oriented 90° from N (=E-W) with grass

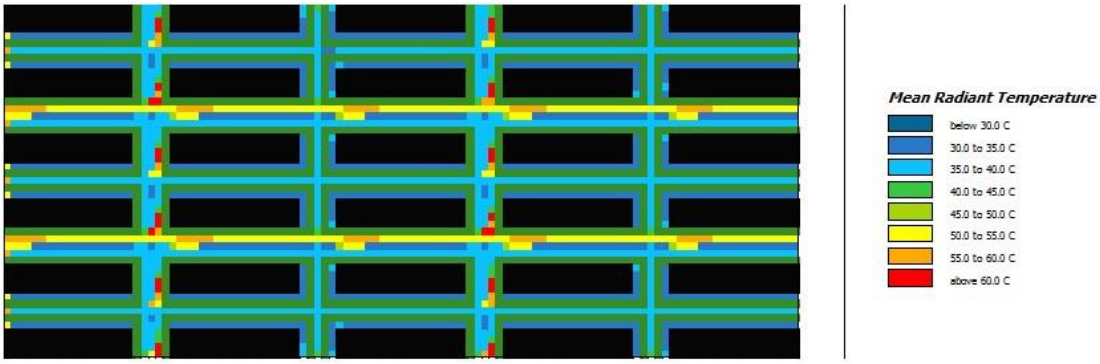


Figure 49. MRT simulation at 14:00 for main streets oriented 90° from N (=E-W) with grass and trees

4.1.4 Model 1, Meireles

The simulation results from Model 1 are presented in Table 3.

Table 3. The simulation results at 14:00 for Model 1. The values are average values for the simulated area.

Simulation	**Wind speed m/s**	**Temp °C**	**MRT °C**	**RH %**	**PMV**
Model 1	1.3	30.5	57.1	67.1	3.9

Model 1 has an average wind speed of 1.3 m/s and a MRT of 57.1°C. These observations can be viewed in more detail in Figure 50 and Figure 51.

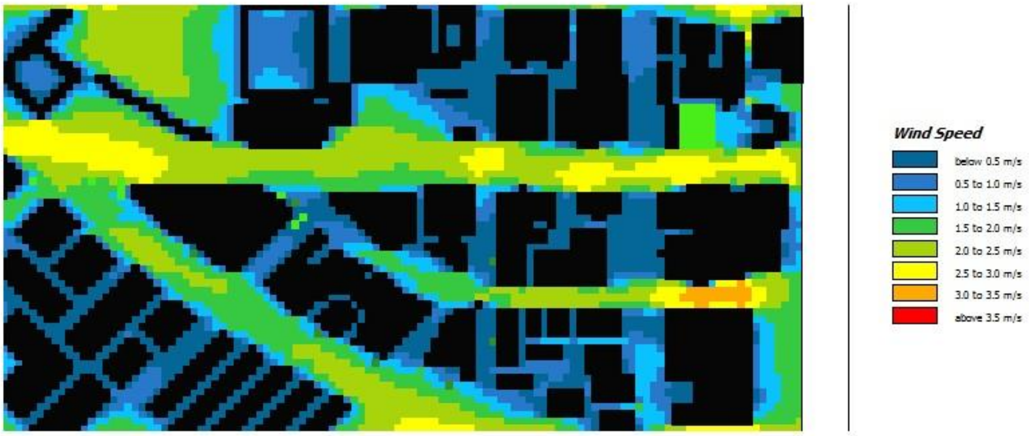


Figure 50. The wind speed simulation at 14:00 for Model 1 with a wind direction at 81°.

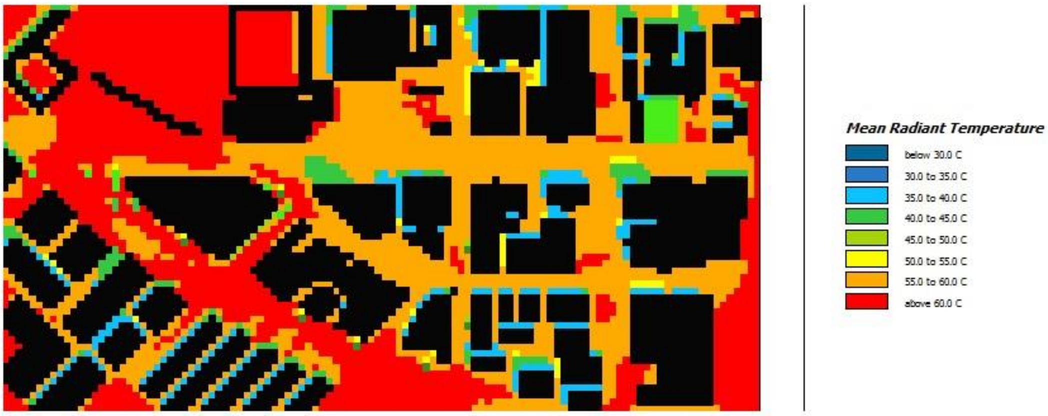


Figure 51. The MRT simulation at 14:00 for Model 1

The wind pattern and main streets in Model 1 are illustrated in Figure 52.

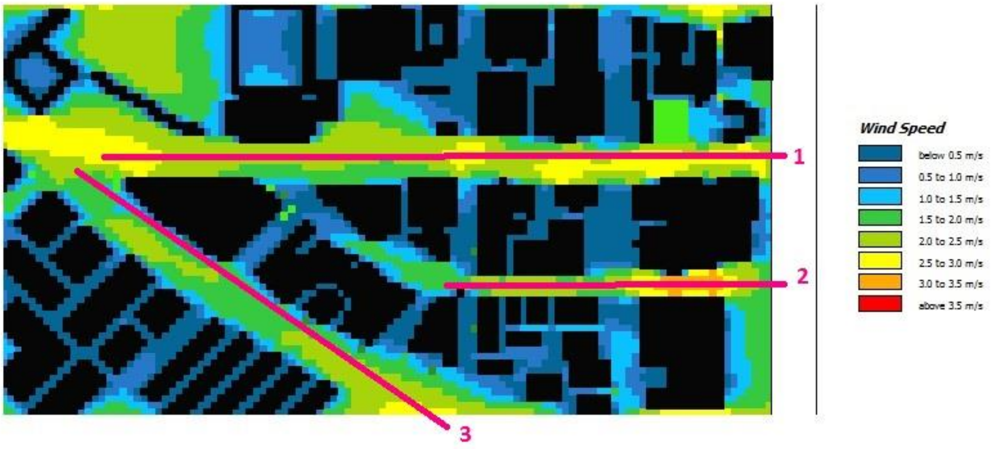


Figure 52 Wind simulation for Model 1 at 14:00 with a wind direction at 81°, showing the main streets: Street 1, Street 2 and Street 3, visualized as pink lines along the streets.

4.2 Shading simulations in Ecotect

The shading of Model 2 was investigated using Ecotect.

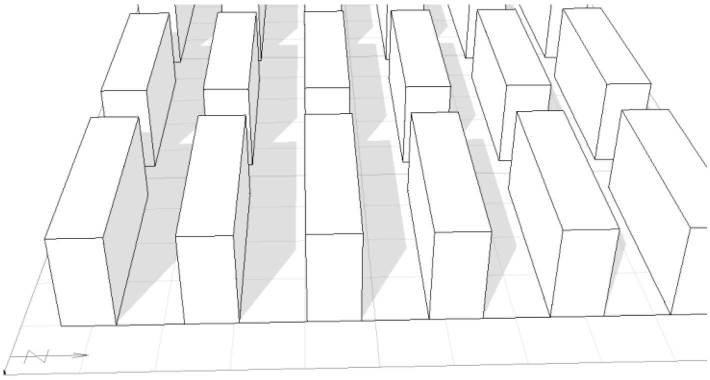


Figure 53. Shading of Model 2 in December between 08:00-09:00.

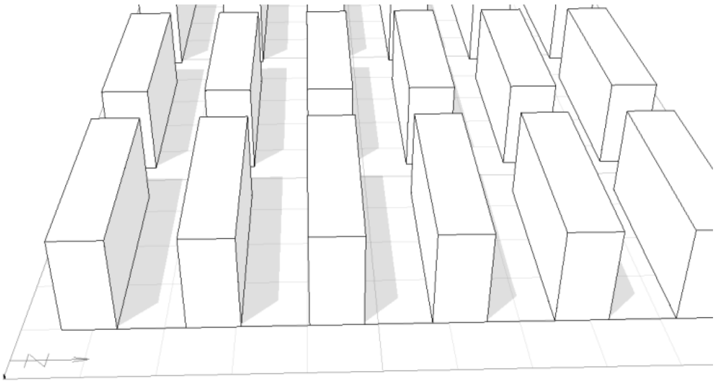


Figure 54. Shading of Model 2 in December between 10:00-11:00.

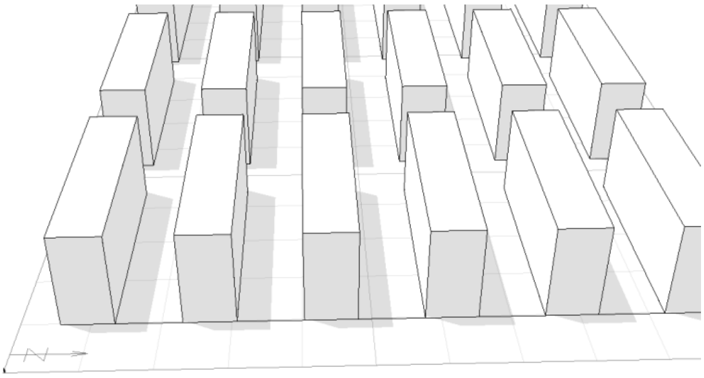


Figure 55. Shading of Model 2 in December between 12:00-13:00.

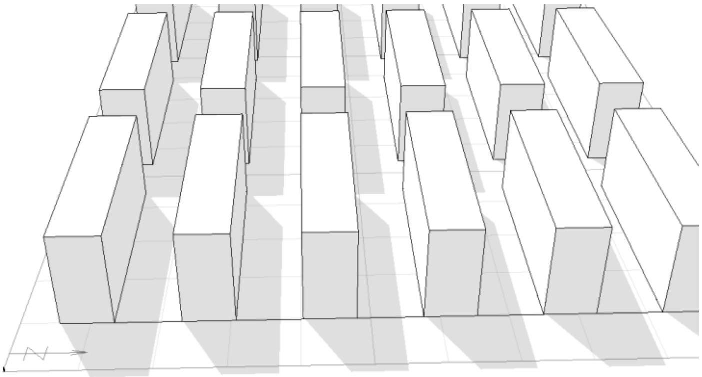


Figure 56. Shading of Model 2 in December between 14:00-15:00.

4.3 Indoor and outdoor measurements in Meireles

Hourly air temperature variations, indoors and outdoors, during three weeks in April (*Figure 57*). The air temperature variation for the outdoor measurements were larger than that of the indoor measurements.

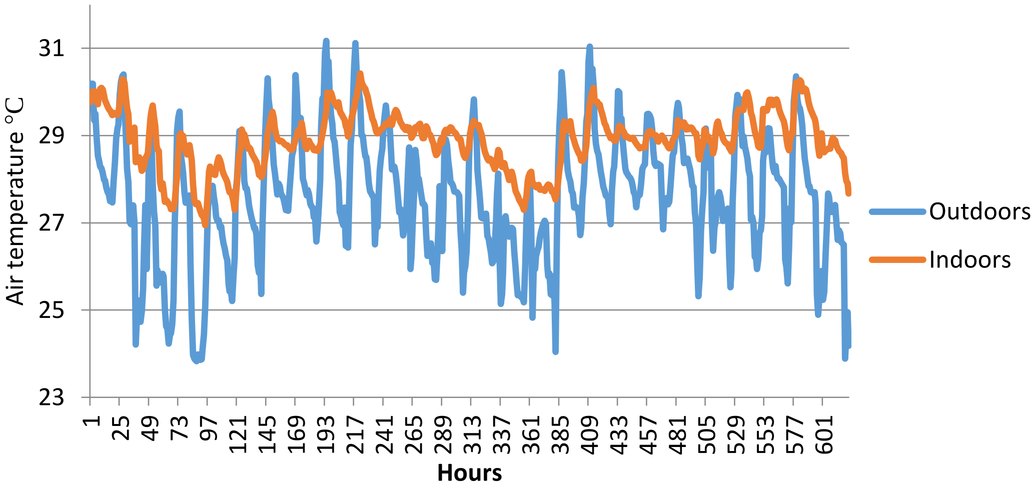


Figure 57 Hourly air temperature data indoors and outdoors in Meireles during the period of 19th of March to 14 of April 2015.

The average hourly temperature for the outdoor and indoor measurements are presented during a whole day in *Figure 58*.

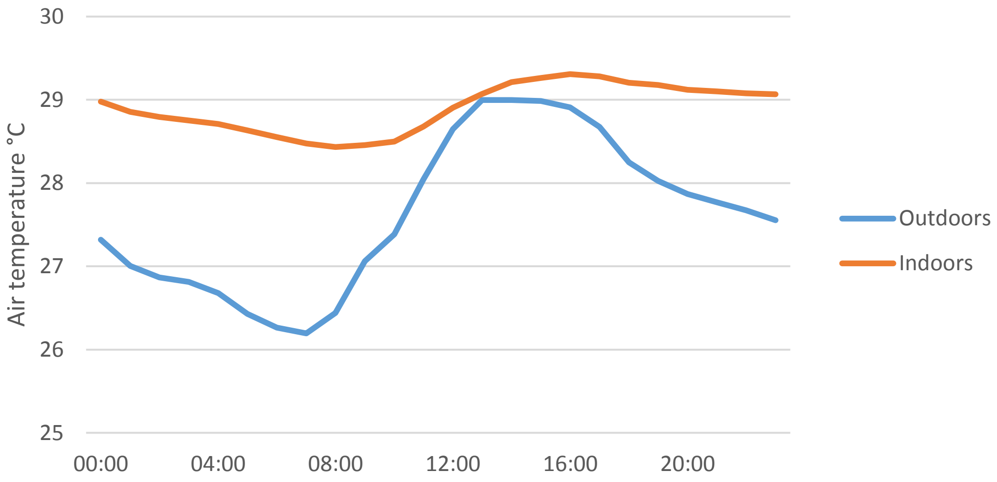


Figure 58. The hourly average air temperature indoors and outdoors during 19 of March to 14 of April 2015 in Meireles.

The maximum, minimum and average air temperature for the whole measurement period for both indoors and outdoors are summarized in *Table 4*.

Table 4 Hourly average-, min- and max temperature from the Meireles measurements indoors and outdoors during the period of 19th of March to 14 of April 2015.

	Outdoor	**Indoor**
Average Temp	27.6°C	28.9°C
Min Temp	23.8°C	27.0°C
Max Temp	31.2°C	30.4°C

The relative humidity (RH) also have a large variation between the indoor and the outdoor measurements where the indoor RH follows the more fluctuating outdoor RH (*Figure 59*).

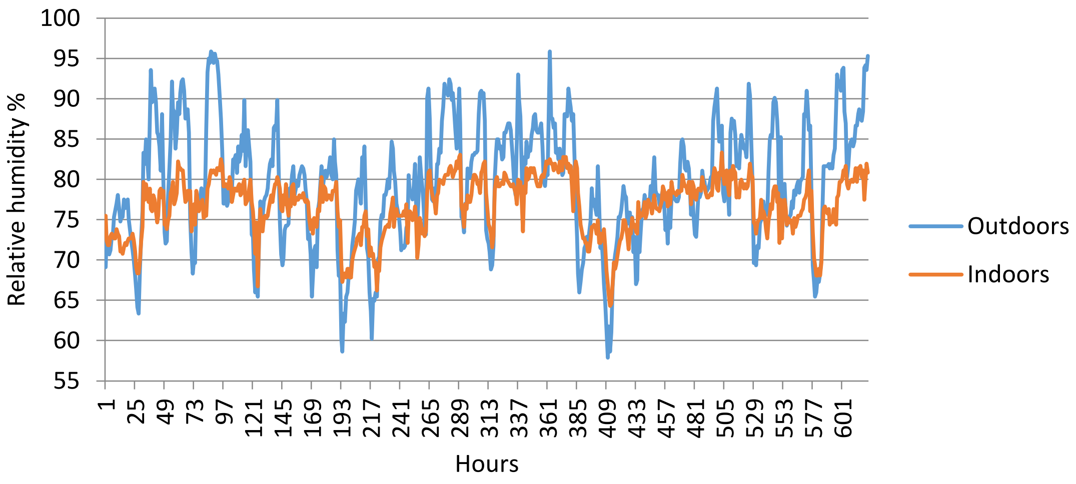


Figure 59 Hourly relative humidity data indoors and outdoors in Meireles during the period of 19th of March to 14 of April 2015.

The outdoor relative humidity peaks at 96 % and has a low relative humidity of 57.85% (*Table 5*). The average relative humidity during this period of time was 79.6% outdoors and 76.8% indoors.

Table 5 Hourly average-, min- and max relative humidity from the Meireles measurements indoors and outdoors during the period of 19th of March to 14 of April 2015.

	Outdoor	**Indoor**
Average RH	80 %	77 %
Min RH	58 %	64 %
Max RH	96 %	83 %

4.4 Cooling degree days

The amount of degree days follow the base temperature in an almost linear relationship (*Figure 60*).

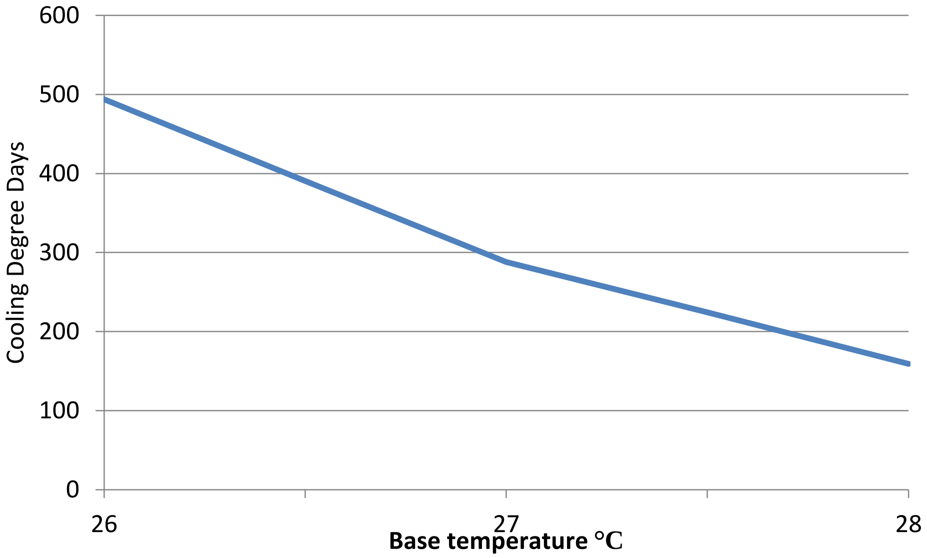


Figure 60 Yearly averaged cooling degree days against base temperature, between August 2012 and July 2015.

The average amount of cooling degree days during a year (*Figure 61*). The data shows a peak of cooling degree days during March at 52 CDD followed by December at 51 CDD and January at 50 CDD. July has the lowest amount of cooling degree days at 28 CDD.

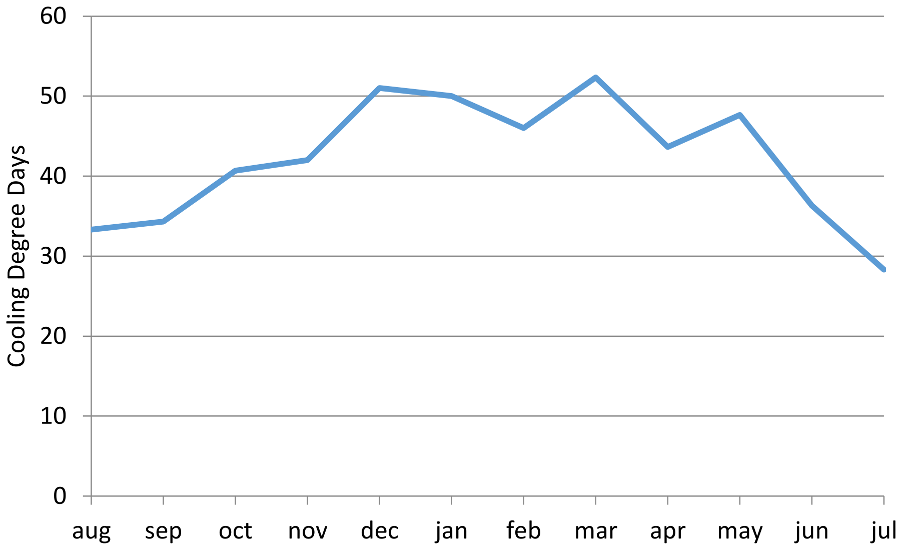


Figure 61. The monthly average number of cooling degree days between August 2012 and July 2015.

By setting a reference base temperature the air temperature decrease of 1 degree can be estimated as the increase of the base temperature by 1 degree, in that case the CDD for such a decrease can be read in *Figure 60*. The results from the simulations show a decrease of 2 °C at 14:00 in December in Model 2. Assuming that this would lead to a 1 °C decrease of the average temperature throughout the year the space cooling reduction can be estimated. Below, two different energy reduction estimations are calculated in Scenario 1 and 2.

Scenario 1: For Fortaleza the average CDD for a year is 495 with a base temperature at 26°C (*Figure 60*). If the air temperature would be reduced by one degree this can also been seen as increasing the base temperature to 27°C. A base temperature at 27°C yields 288 CDD. Resulting in a space cooling reduction of 42%.

Scenario 2: With a base temperature at 27°C the average CDD for a year in Fortaleza is 288 (*Figure 60*). Lowering the temperature one degree is similar to increasing the base temperature to 28°C which yields 159 CDD resulting in a space cooling reduction of 45%.

4.5 Storm water management

4.5.1 Catchment area

The direction of storm water flow was mapped in SketchUp (see Figure 62 and Figure 63). The total size of the catchment area was found to be approximately 505 600 m^2 (Figure 64).

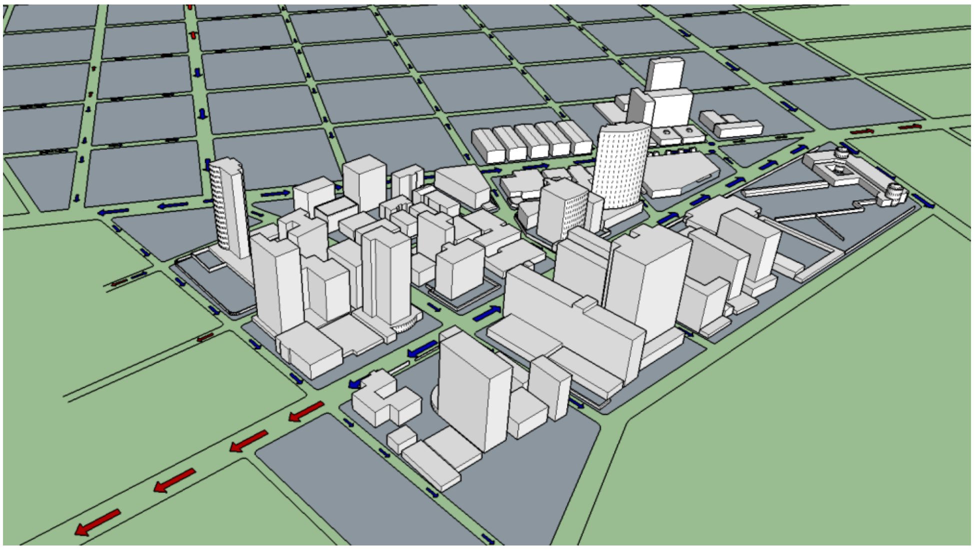


Figure 62. Model 1 (white) from a north eastern angle. Storm water runoff inside catchment area (blue) and outside catchment area (red).

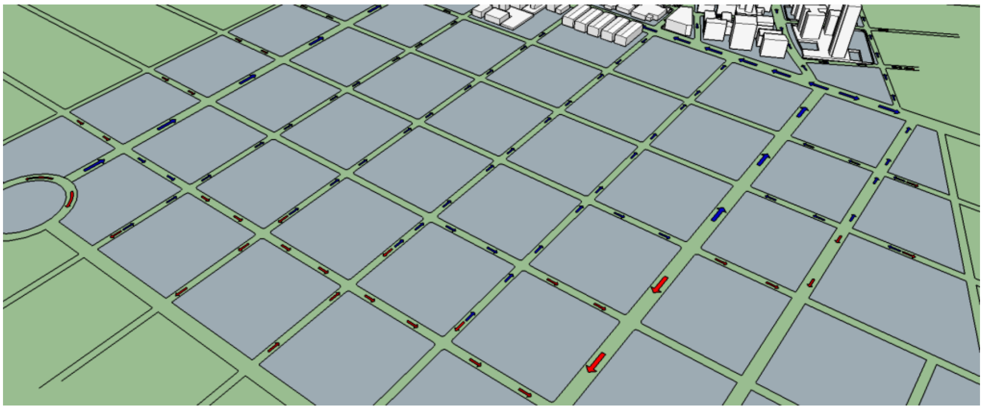


Figure 63. Model 1 (white) from a south eastern angle. Storm water runoff inside catchment area (blue) and outside catchment area (red).

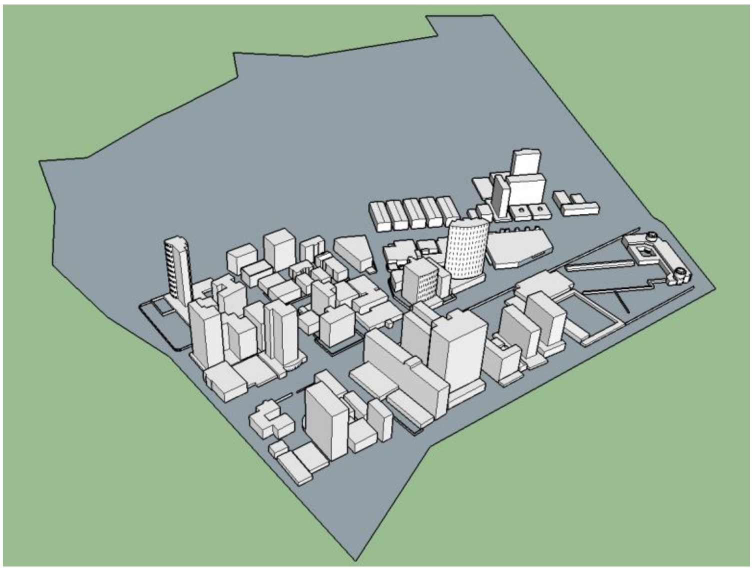


Figure 64. Model 1, (white) and total size of catchment area (grey).

4.5.2 10-year rainfall

The top three largest rainfalls was found to be 197.6 mm, 197.5 mm and 173.8 mm respectively. The average value of the three rainfalls, and thus the assumed 10-year rainfall, was calculated to be 189.6 mm. This value was used in the calculations of storm water runoff.

4.5.3 Runoff volume and floodplain depth

The total runoff volume in the catchment area was calculated to approximately 95 860 m^3. The total runoff volume in Model 2 alone was calculated to approximately 25 550 m^3.

If Model 2 would take care of the water in the whole catchment area the depth of the floodplains would be required to be approximately 2.4 m. The floodplain depth would be required to be 0.6 m if only the storm water in the area of Model 2 had to be retained.

5 Discussion

5.1 Influence of Aspect ratio on microclimate

When simulating for different aspect ratios, the wind flow in ENVI-MET was found to show a very different behavior than found in previous research and the accuracy of ENVI-MET´s wind simulations are uncertain. A numerical study, using a potent fluid modelling tool called Computational Fluid Dynamics simulations (CFD), (Wong, 2005) showed that the wind flow in an urban canyon parallel to the wind flow reaches its maximum velocities on an aspect ratio of 0.4 (due to undisturbed wind flow) and on 1.5 due (to the channeling effect). The wind speed in ENVI-MET was found to show a small but steady increase from H/W=0.48, peaking on H/W=1.2 and then decreasing again. The difference in wind behavior between ENVI-MET and previous research indicated that ENVI-MET was not an ideal program to simulate wind flow in three dimensions, and instead the data from the numerical study was used. Wind flow is one of the most important factors when designing for a good thermal comfort in a hot humid climate, so when choosing between shade of sidewalks and wind optimization, wind may be more important (Givoni, 1998). Thus the wind flow was considered primarily when choosing an aspect ratio for the subsequent simulations.

The MRT and the air temperature showed a linear decrease with increased aspect ratio. A decrease in mean radiant temperature and air temperature with increased aspect ratio was expected due to shading from the adjacent buildings. The average MRT of the area decreased by more than 10 degrees (from about 58°C to 47°C) and the average air temperature decreased by about 2°C between aspect ratio 0.4 and 1.5. The aspect ratio of 1.56 was chosen for the subsequent simulations because, according to the literature, it would have similar wind speed as 0.48 but induce a lower air temperature and a much lower MRT which has a significant positive effect on the thermal comfort.
This study did not consider different aspect ratios for the parallel and perpendicular streets, but had the same aspect ratio for both. Streets perpendicular to the wind flow should have an aspect ratio of 0.25 or less (Aynsley & Gulson, Microclimate and Urban planning the humid tropics, 1999) to maintain an adequate wind flow. The wind speed in the perpendicular streets is thus considerably lower than in the parallel streets. This will have affected the average wind speed value as well as the average PMV value in the area. However, the total area between the buildings in the perpendicular streets is small compared to the total street area thus having a small effect on the average values.

The simulations in this project has had the same height on all the buildings in the area. However, this is not desirable because a uniform urban canopy will separate the wind flowing above the urban canopy from the air below (Aynsley & Gulson, 1999). This leads to a low mixing of air between the layers and lower wind velocities at street level. It is therefore preferred to have a non-uniform urban canopy to facilitate the mixing of air between the layers (Givoni, 1998). When choosing an aspect ratio it should be seen as an average value over a larger area, instead of a target value for each and every street. Another factor that could significantly improve the wind and air temperature conditions at street level is the use of towers; high-rise buildings spread out in the area. Towers, if properly designed and placed could bring down cool air from higher altitudes and significantly increase wind speed in the streets, further improving the area´s thermal comfort conditions. Fortaleza has an uneven urban canopy with high-rise towers of different heights. But the towers are placed close to each other, thus the downwash effect from the towers is small. The average height of the canopy is also high where streets with aspect ratios between 3 and 5 are common. Instead of improving the wind conditions at street level through the downwash effect the towers create a wall blocking the wind and the high urban canopy-layer inhibits the mixing of air.

5.2 Influence of vegetation on microclimate

Replacing a part of the asphalt with grass resulted in both a lower air temperature and a lower MRT. The air temperature decreased by 0.8 °C due to a cooler surface temperature of the ground which is heating the air at ground level. The MRT decreased by 3 °C due to a lower amount of long wave radiation from the cooler grass surface which is consistent with the hypothesis.

The increase in wind speed, from 2.4 m/s to 3.1 m/s was unexpected and there seems to be no logical explanation to this. The increase may have been caused by an error in the simulation or a programming fault by ENVI-MET. The wind speed was expected to be unaffected because the only difference between the two cases is a slightly larger roughness of the grass compared to asphalt which would only have a small effect and could be neglected. The total ground area was covered to 50% by grass. The air temperature could have been lowered further by increasing the surface area covered by grass. Grass also increased the RH by 4%. The increase is probably due to both the increase in humidity resulting from the evaporation from the grass surface and the decrease in air temperature.

The use of trees significantly decreased the average wind speed in the area from 2.4 m/s to 1.6 m/s. The ground area was covered to 42% by trees. 15 m high, dense trees with a leafless base was chosen as they would have little effect on the wind on ground level, but instead proved to have a significant negative effect. The results indicates that even taller trees would be preferable to mitigate the wind obstruction. No information is provided of the shape of the trees. The tree crown in ENVI-MET may have a spherical shape whereas in this case a flat tree crown would be ideal. There is no possibility of changing this factor in ENVI-MET. Perhaps it would be possible to achieve the same or lower MRT and air temperature while using fewer trees but better placed, thus having a smaller effect on the wind speed. The relative humidity increased further by about 8% with the use of trees for the same reasons as for the grass.

The increase in relative humidity and the significant decrease in wind speed caused by the use of both trees and grass should cause a decrease in thermal comfort, since they are both important factors. But the decrease in air temperature and mean radiant temperature led to an improvement of thermal comfort from a PMV value of 3.3 without vegetation to 2.9 with grass and 2.4 with both grass and trees. According to the PMV scale the thermal comfort conditions went from above “hot” to slightly above “warm”, or in other words: a 21% decrease in thermal discomfort with the use of grass and trees.

5.3 Influence of street orientation on microclimate

The results show that there is a slight difference in wind speed between the streets oriented parallel to the prevailing wind and the streets oriented 30°S to the prevailing wind. The street parallel to the wind has a higher wind speed of 0.3 m/s (2.4 m/s compared to 2.1 m/s). The change in wind speed did not affect the thermal comfort since the resulting PMV value is identical at 3.3.

The different orientations of streets together with vegetation show no or very small differences in wind speed compared to each other. This may be because the large amount of trees obstruct wind to such a degree that the differences in street orientation become trivial. Even though the simulations for different orientations which included vegetation had a low average wind speed (1.6 m/s), they have the best PMV values at 2.4. The 0° oriented street was predicted to have a higher wind speed than the 30° oriented street and a low wind speed should result in a high PMV. The low PMV is probably due to the shading effect from the trees and indicates that shading is a more important climatic parameter than wind for thermal comfort, at least at this magnitude of wind speed. The small differences in wind speed observed between the two street orientation simulations with vegetation implies that the 30°S orientation is preferable since the benefits for a street oriented to provide natural ventilation for buildings has a positive effect on the cooling load. The simulation of street orientation tilted 30°S was conducted by changing the angle of incidence of the wind to the model. If the model had been rotated 30°S instead it is likely that the resulting value of MRT and air temperature would be different due to a different amount of solar radiation reaching the streets. However, the difference would probably be small because of the high position of the sun at mid-day.

The orientation of streets in the simulations were limited to having the side streets, fixed perpendicular to the main streets. It is possible that the wind conditions of the side streets could be improved by having a different angle towards the main streets. If the main streets were oriented with a 30° tilt to the south and the side streets were oriented parallel to the eastern wind, good wind and natural ventilation conditions could be achieved in the main streets and optimal wind conditions could be achieved on the side streets. This study is limited to only investigating a 30° angle to the prevailing wind while studies suggest that good ventilation conditions could be achieved between a 10° and 30° angle. It is possible that by testing other street orientations that were not tested in this study a more optimal solution could be found.

The analysis from Ecotect shows good shading conditions during the day on the main streets parallel to the main wind flow (Figure 55 and Figure 56). This is consistent with literature that states that for locations near the equator, an east-west orientation minimizes sunlight on façades (Schiller & Evans, 1998).

The street orientation simulations suggest that wind speed is not significantly affected by changes in street orientation which suggests that an orientation of the streets of 30° to the south can be used to optimize natural ventilation for buildings without conflict with the thermal comfort. It is possible that optimizing for natural ventilation of buildings could decrease the air temperature even further since the use of AC would be reduced and thus emit less heat to the outdoor environment.

5.4 Simulations of Model 1, Meireles, Fortaleza

Although ENVI-MET may not be completely reliable regarding wind flow simulations the results show a significant difference between Model 1 and 2. Model 1 (Meireles) showed a low average wind speed of 1.3 m/s compared to the Model 2 without vegetation with 2.4 m/s. The simulations with vegetation in Model 2 is still higher than the average wind speed than that of Model 1. It seems unlikely that a better street orientation of Model 2 solely contributes to such a large difference since the orientation of the streets are quite similar to Meireles main streets. Street 1 and Street 2 have a street orientation of 9°N to the prevailing wind flow (Figure 52). However, Street 2 has a sharp bend obstructing the wind and decreasing the wind flow significantly, indicating the importance of straight streets. Street 3 has approximately a 30°S angle to the prevailing wind direction (Figure 52) but shows a lower wind speed compared Model 2 without vegetation. It is feasible to consider that the urban geometry is a large contributor to the lower wind speeds of Meireles. Meireles has an air path geometry (see Canyon Geometry 2.2.1) of approximately 0.25 compared to the Model 2 of 0.625 (Table 7. Data for the storm water calculations). Ng (2010) states that air path geometry should preferably have a value of 0.5 or above. The poor air path geometry may be a large contributor to the lower wind speeds observed in Meireles. The ground coverage ratio (GC) is roughly correlated to the geometry of air paths and Meireles has a GC of 0.6 compared to 0.4 in Model 2 (Table 6 appendix). An increase of GC from 0.3 to 0.6 generally decreases the wind speed by half (Ng, 2010) which could be due to an increase of stagnant zones. The average wind speed of Model 2 is 2.4 m/s and 1.3 m/s for Model 1 which is consistent with the difference in GC. In conclusion, from a cross ventilation perspective, the urban area in Meireles has been planned inefficiently. By improving the urban design of Meireles the wind speed could be increased significantly. It is also worth mentioning that a number of the side streets in Meireles have an unfavorable SW-NE orientation which, as the wind originates from an E or SE direction, will inhibit wind flow. Additionally, the high aspect ratio makes the side streets exposed to a skimming effect causing a lack of air mixing.

With little vegetation in Meireles it can be assumed that an increase of urban greenery would decrease the wind speed even further. When addressing the need for shade, it is important to consider where to place vegetation in Fortaleza to avoid further decrease in wind flow.

5.5 Reflections of the simulations

In this project, the single design day was chosen to be a day in mid-December, the hottest month of the year, at two o´clock in the afternoon. The thermal comfort in many areas in Fortaleza is bad, and in some cases even hazardous, during several hours of the day. Two o´clock was chosen as it is the hottest hour of the day but perhaps it is more important to improve the thermal comfort at the hours when people spend the most time outdoors. By improving the thermal comfort for the hottest hour during the hottest period of the year, the “worst-case” scenario would be accounted for and the rest of the year would experience an even better thermal comfort. However, the simulations had a constant wind, thus not simulating for calm wind conditions where the thermal comfort could be much worse.

Another aspect that was not regarded in this project was the Ground Coverage ratio (GC). Higher ground coverage is correlated to a decrease of the wind speed in the area. The ground cover ratio in Model 1 is 0.6 and the ground cover in Model 2 is 0.4 which indicates that Model 1 is using up more space for buildings. The difference in ground cover ratio could have affected the results and changed the difference in PMV between Model 1 and the final results in Model 2. By having the same ground coverage ratio in both models, the validity of the results comparing Model 1 and Model 2 could have been enforced.

The size of the area could have affected the results in a major way since the microclimatic conditions are deteriorating further inside the city. A larger area could have reduced the errors and given more realistic results. The wind speed is likely to decrease deeper into the city which was not seen in the simulations. Either the street geometry of Model 2 provided adequate mixing of air between the UCL and the RS and sufficient air paths or the area was too small for the wind decrease to be seen.

It is important to know that the improvement of the three microclimatic factors that was made in this project, wind speed, MRT and air temperature, are local changes and will have an insignificant effect on surrounding areas. In order to accomplish the same results as accomplished in this project on a larger scale, the design criteria has to be adopted to a large part of the city.

One major simplification in Model 2 was house and street design. Long rectangular buildings was used, each separated by a wide street. The example was used to be able to evaluate the effect of aspect ratio, street orientation and vegetation on the thermal comfort. In order to improve the thermal comfort further other building designs could have been used, for example aerodynamic buildings or buildings put on pillars that lets the wind pass by underneath.

By designing an urban area with the three design factors discussed in this project in mind, aspect ratio, street orientation and vegetation, the thermal comfort conditions could be greatly improved. An improvement of the thermal comfort could change the behavior of the people in the city. It could become more comfortable to move outside, walk or take the bike to work which in turn could result in other benefits such as improved health and less traffic. Retro-fitting an area is not as easy and cheap as having the design criteria in mind already in the planning phase of an urban area which emphasizes the importance of incorporating this knowledge into building standards and regulations when building a sustainable city.

5.6 Reduced Energy for space cooling

The simulations from Model 2 show that the temperature can be lowered significantly in Fortaleza by introducing vegetation strategically. The experienced temperature is lowered by orienting the streets towards the prevailing wind flow by removing skin wetness. It is problematic estimating exactly how much energy is saved by designing for a better microclimate. Many parameters should be taken into consideration regarding the climate outdoors, climate indoors, building design and the efficiency of mechanical cooling. To provide an accurate estimation of the space cooling savings, measurements of the cooling load is needed but in reality this would be insufficient as well since buildings differ from each other. One way of estimating the space cooling load is by measuring the cooling degree days needed for a certain base temperature. The back of the envelope calculations from Scenario 1 and 2 show potential of significant energy reductions by smart microclimatic design. However the energy savings provided in Scenario 1 and 2 are highly speculative for many reasons but they do actually stand in agreement with other studies and estimations. Lovins estimates that Los Angeles with simple microclimatic solutions can reduce space cooling by 20%, Parker shows that buildings in Singapore next to strategical placed vegetation can reduce space cooling by 50%.

The indoor and outdoor measurements from Meireles shows that the indoor air temperature has a higher average temperature than outdoors, the peak air temperature are highest outdoors though. It is interesting to observe that the air temperature difference between 00:00 and 06:00 is approximately 2°C lower outdoors at this time. It is normal for the air temperature outdoor to be more variable than the indoors since the buildings have a higher heat capacity than the outdoor environment. But it is not desirable that the indoor air temperature in the evening is higher than the average peak air temperature outdoors. Solar shading on the facades of buildings and the choice of building material may have a positive impact on the indoor thermal comfort.

Even though there is a lot of cooling potential by adding vegetation to the area and increase of thermal comfort by orienting the streets towards the prevailing wind flow there will still be times when external cooling is needed. Both the measurements in Meireles, the estimation of cooling degree days and the psychometric chart indicate that external cooling is needed. However, cooling an apartment separately with an air condition system might not be the optimal solution. Instead direct cooling has a lot of benefits for large scale cooling (Kee, 2010). One possible direct cooling solution would be to utilize “free cooling” from the deep ocean (Svensk Fjärrvärme, 2015).

5.7 Storm water management in Fortaleza

It is clear that having a storm water management system to retain and treat the storm water before reaching the ocean is important to a city like Fortaleza. The heavy tropical rains combined with a dense, heavily trafficked urban area gives rise to large volumes of runoff and pollutants reaching the ocean and the beaches.

Due to that the three most heavy rainfalls were of a similar magnitude it was difficult to conclude that the largest rainfall was a 30-year rainfall, the second largest a 15-year rainfall and the third largest a 10-year rainfall. This indicated that the method of calculating an average out of the three rainfalls could be appropriate with the given data. If calculations were to be made of transport of water out of the system into the ocean over time, the duration and intensity of the rainfalls would be of highest significance. However, the aim of the study is only to discuss if the total volume of a 10-year rainfall can be retained in the vegetated areas without any outlet to the ocean, thus the duration in hours during a day is irrelevant. All storm water was assumed to become runoff, which in reality is not true. No regard was taken to the fact that some water is stored in cavities, on the surface of the urban material or by interception of trees. Due to the size of the rainfalls, the loss of water due to these factors could be assumed to have an insignificant effect on the total runoff volume, but for a more detailed study these are important factors to consider.

The total amount of water falling in the catchment area during a 10-year rainfall was found to be substantial and would require the floodplains in Model 2 to have an average depth of 2.4 m. This depth may not be realistic in the narrow streets which are used for car traffic and pedestrians. If Model 2 would have to deal with only the storm water falling in the area of Model 2 the average depth of the floodplains would be required to be about 0.6 m, which is more realistic.

Evaporation in Fortaleza is approximately 4.5 mm/day. It would require more than just evaporation to get rid of the water in an acceptable time period. Ground material that provide good infiltration and trees that are able to quickly absorb large amounts of water could be used for this purpose. Evaporation from the floodplains could temporary increase the humidity of the urban area which in turn could decrease the thermal comfort. However, due to the proximity to the Atlantic Ocean the increase in humidity could be regarded as insignificant.

The results show that the runoff volume from a 10-year rainfall could be retained in the area of Model 2 through the use of floodplains if the area only had to deal with its own storm water. This indicates that storm water must be retained and treated on-site in every part of the city. However, due to that the area is closely located to the ocean, excess water from larger rainfalls could be directed there in order to avoid floods. The water should be treated before reaching the ocean in order to not let pollutants reach the ocean. Water could be treated by flowing through certain pollution filters or to use a so called “first flush”-system.

There are many other ways of dealing with storm water which could be combined with the floodplain system. For example by flooding parts of the streets to a certain level without obstructing area usage, using green roofs or by temporary storing water on rooftops, passively reducing the cooling load of the building. Designing urban areas to improve the outdoor thermal comfort may not be conflicting with designing a storm water management system. The two could be combined and even be beneficial to each other.

5.8 Concluding remarks - recommendations for Fortaleza

Although the main streets of Meireles and other parts of Fortaleza have good orientations in respect of wind flow, the breezeways into the central business district, CBD, are few and not optimal. Only two of the main streets from the eastern shore stretch all the way into the city center but both unfortunately have sharp bends deflecting the wind. With the CBD approximately 6 km from the eastern shore the wind has to travel a considerable distance before reaching the city center, thus severely limiting the wind flow into the area due to wind obstructions and a high surface roughness. It would be beneficial to have a majority of the main streets in the CBD straight all the way to the eastern shore. Perhaps the most optimal design would be to have placed the city along the eastern shore but in a retro-fitting perspective this is highly unrealistic, however it shows of the importance of microclimatic design in an early planning stage. A possible retro-fitting solution is to improve the thermal comfort of Fortaleza by planting trees along the sidewalks. Adding vegetation could also be combined with the storm water management system in order to decrease the runoff reaching the ocean.

Another important aspect is to not place buildings too densely along the shore which would allow for more wind to pass through the city. The closer to the shore the more important it is for the buildings to be aerodynamic allowing wind to pass through. Many of the higher buildings are standing on large podiums which inhibits the downwash effect. The podiums increases the ground coverage ratio, thus decreasing the wind speed on ground level while using the building space inefficiently.

It would be beneficial to utilize the large park Cocó acting as a climate control providing natural cooling. Cocó is a large park following the river Cocó which flows through the city (Figure 2). The park is a great resource for the city from a microclimatic perspective because of its large size. However, today the CBD is placed far away from the park and its air paths is not linked with the park.

With an exponential urban expansion in tropical climates the need for smarter microclimatic cities is of great importance. They can mitigate the effects of climate change, improve thermal comfort, provide significant reductions in space cooling and protect against floods and pollution.

5.9 Further research

It would be interesting to investigate the effect of ground coverage ratio on the climate conditions, and how it is used optimally in the city. This report also calls for further investigations on other urban design factors such as wind towers and their cooling potential for cities. From an urban energy perspective it would also be interesting to investigate the free cooling potential from deep sea cooling of coastal cities at the equatorial line.

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7 Appendix

7.1 Input data for ENVI-MET simulations

The data below was used in the configuration file for the simulations in ENVI-MET.

```
%MAIN-DATA -------------------------------

Start Simulation at Day (DD.MM.YYYY):       =18.12.2014
Start Simulation at Time (HH:MM:SS):        =06:00:00
Total Simulation Time in Hours:             =13.00
Save Model State each ? min                 =60
Wind Speed in 10 m ab. Ground [m/s]         =4.14
Wind Direction (0:N..90:E..180:S..270:W..)  =90
Roughness Length z0 at Reference Point      =0.01
Initial Temperature Atmosphere [K]          =297
Specific Humidity in 2500 m [g Water/kg air] =19.00
Relative Humidity in 2m [%]                 =70
Database Plants                             =Plants.dat

[SOILDATA] ________________________________________Settings for Soil
Initial Temperature Upper Layer (0-20 cm)   [K]=295
Initial Temperature Middle Layer (20-50 cm) [K]=296
Initial Temperature Deep Layer (below 50 cm)[K]=297
Relative Humidity Upper Layer (0-20 cm)       =70
Relative Humidity Middle Layer (20-50 cm)     =70
Relative Humidity Deep Layer (below 50 cm)    =70

[BUILDING]____________________________________Building properties
Inside Temperature [K]                  =300
Heat Transmission Walls [W/m²K]         =2
Heat Transmission Roofs [W/m²K]         =2
Albedo Walls                            =0.4
Albedo Roofs                            =0.3

[LBC-TYPES] __________________________________________Types of lateral
boundary conditions
LBC for T and q (1:open, 2:forced, 3:cyclic)  =1
LBC for TKE (1:open, 2:forced, 3:cyclic)      =2

 [TIMESTEPS] ____________________________________Dynamical Timesteps
Sun height for switching dt(0) -> dt(1)      =0
Sun height for switching dt(1) -> dt(2)      =20
Time step (s) for interval 1 dt(0)           =10
Time step (s) for interval 2 dt(1)           =10
Time step (s) for interval 3 dt(2)           =5

[CLOUDS] ________________________________________

Fraction of LOW clouds (x/8)            =4
Fraction of MEDIUM clouds (x/8)         =0
Fraction of HIGH clouds (x/8)           =0
```

[SOLARADJUST] ____
Factor of shortwave adjustment (0.5 to 1.5) =1.15

[PMV] ____Settings for PMV-Calculation
Walking Speed (m/s) =0.3
Energy-Exchange (Col. 2 M/A) =116
Mech. Factor =0.0
Heattransfer resistance cloths =0.5

7.2 Model and storm water data

The width of the buildings at the edges of the street is 50-60 m. The width of the main street in Meireles is 30m. The air paths of Model 1 and 2 were calculated by dividing the width of the street with the total width of the two adjacent buildings ($\frac{Ws}{Wb}$). The results are presented below in Table 6.

Table 6. Area, GC, Air path and Grass cover for Model 1 and 2

Model 1	
Area	173 250 m^2
Ground cover (other name?)	0.6
Air path geometry	0.25
Model 2	
Area	134 750 m^2
Ground cover	0.4
Air path geometry	0.625
Grass cover	40 520 m^2

Table 7. Data for the storm water calculations

Storm water	
10 year rainfall	189.6 mm
Catchment Area	505 590 m^2
Total runoff volume catchment area	95 860 m^3
Total runoff volume Model 2	25 550 m^3
Required floodplain depth, full catchment area	2.4 m
Required floodplain depth, Model 2	0.6 m
Evaporation	4.5 mm/day

7.3 Average wind speed calculation

The wind rose for December, shows that the average wind speed is, 6% 1.3 m/s, 20% 2.83 m/s, 41% 4.65 m/s and 7.25 m/s. Resulting in an average wind speed from the east of 4.14 m/s.

7.4 Cooling degree days

Information that was used to generate the degree days provided in Table 8.

Table 8 Information used to calculate cooling degree days.

Description:	Celsius-based cooling degree days for a base temperature of 26.0C
Source:	www.degreedays.net (using temperature data from www.wunderground.com)
Accuracy:	Estimates were made to account for missing data: the "% Estimated" column shows how much each figure was affected (0% is best, 100% is worst)
Station:	Fortaleza / pinto Martins, BR (38.53W,3.78S)
Station ID:	SBFZ