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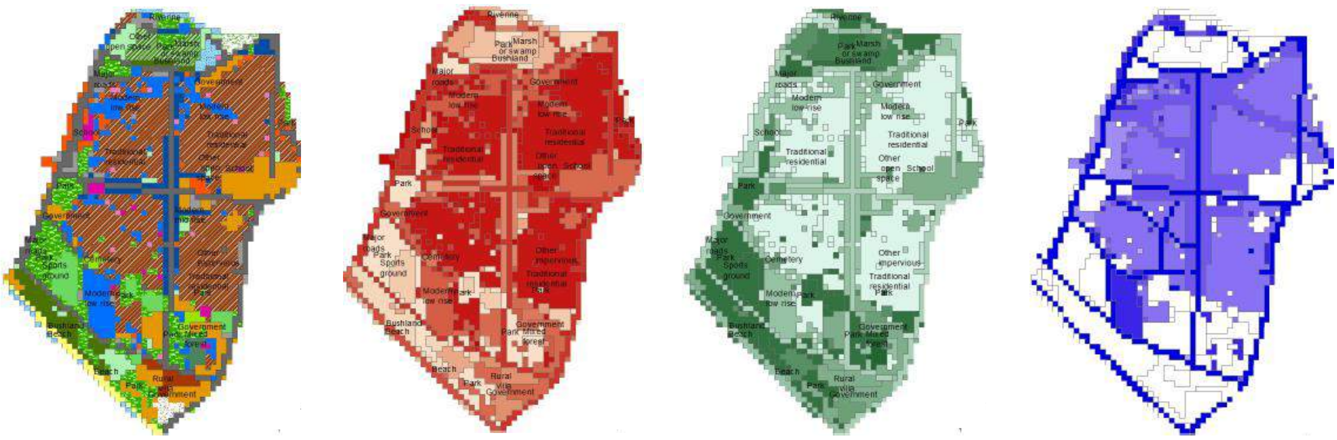

AN URBAN CLIMATE MODEL FOR USE IN STRATEGIC ENVIRONMENTAL ASSESSMENT

Case: Creating a Climate Change Resilient Ng'ambo, Zanzibar City

Master's Thesis in Industrial Ecology

MAIKE LÜHR

Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2016
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Supervisor and Examiner: Sverker Molander

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Department of Energy and Environment
Division of Environmental System Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0) 31-772 1000

Cover: Modelling results from the urban climate model STAR tool visualized in ArcGIS

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Abstract

The urban climate has become a vital consideration for many populations as the effects of climate change are becoming increasingly prevalent. The climate in cities is different compared to rural areas, not least because of the minimal vegetation and the characteristics of building materials. As cities are getting hotter and heat-related mortality is increasing, eyes of urban planners and politicians are turning towards the necessity of climate change adaptation. The responses turned to often involve downscaling climate change projections to cover the local climate in order to have a basis for local adaptation strategies. However, within the scientific field of urban climatology, the differences between urban and rural temperatures have been documented and observed for over 100 years. The use of this knowledge could lead to more effective and site-specific climate change adaptation measures in city planning. To effectively integrate urban climatology into adaptation strategies it needs to be addressed at an early stage. An available methodology that could embrace these issues is for example Strategic Environmental Assessment (SEA), an internationally accepted and standardized tool which is adaptable to a broad variety of contexts.

Developing countries are more vulnerable to, and also face the highest projections of, climate change. Here adaptation measures are needed that are economically, socially and environmentally justifiable whether projected climate hazards occur or not. Again, SEA might prove to be a viable tool for finding these low-key adaptation measures. This study does not perform an SEA, but borrows its methodology and structure in a case study performed on the archipelago of Zanzibar. Within this methodology an easy-accessible urban climate model is used which makes the expertise of urban climatology available to urban planners and non-climate-experts.

The study shows that increased vegetation and water, together with reduced building density and mass, can cause significant temperature reductions in urban areas. These differences are actually larger than the expected temperature increases due to global warming. Even though a simple model is used and the results need to be more thoroughly verified, the outputs can provide rough guidance early in a planning process. The main recommendation reached in the case study include ensuring a surface cover composition that encompasses a high degree of vegetation. Further it is recommended to consider building mass and density and finally to give the climatic properties of buildings materials some thought.

Keywords: strategic environmental assessment, climate change adaptation, urban climatology, developing countries, urban planning, STAR tool, sustainable development, land use change, surface temperature, urban climate modelling,

Preface

This research was conducted as a Master's thesis of 30 credits within the programme Industrial Ecology. It was carried out during the autumn of 2015 and spring 2016. Two months were spent on the main island of the archipelago of Zanzibar, Unguja, at the local planning office, the DoURP, conducting field studies for the case study. I am very grateful for the opportunity given, and the time invested in me.

This research has been extremely educational for me, and I hope it can be of some benefit to others. I hope especially, that it can indirectly benefit the many, beautiful and happy people of Zanzibar that are living in difficult circumstances.

Acknowledgements

I am very grateful to the following people who have contributed significantly to this thesis: Sverker Molander - for his guidance, supervision and comments throughout; all the lovely people at the DoURP - for their warm welcome and helpful attitude; Ben Polmear and Mia Callenberg - for our adventure on Zanzibar; and finally Frederike Leclerc - for her time, interest and thorough proof-reading. I also thank SIDA for funding the case study.

Maike Lühr,
Master's of Science student Chalmers University of Technology

List of Abbreviations

ArcGIS A geographic information system for working with maps and geographic information

DoURP Department of Urban and Rural Planning

EIA Environmental Impact Assessment

EU European Union

GHG Greenhouse gas

HTC Human Thermal Comfort

IPCC Intergovernmental Panel on Climate Change

ITCZ Inter-tropical Convergence Zone

LCZ Local Climate Zones

LST Land Surface Temperature

LULC Land use and land cover

LUMPS Local-scale Urban Meteorological Parametrization Scheme

MRT Mean Radiant Temperature

SEA Strategic Environmental Assessment

SEB Surface Energy Balance

SIDA Swedish International Development Cooperation Agency

SKV Sky View Factor

SVAT Soil Vegetation Atmosphere Transfer

UCL Urban Canopy Layer

UHI Urban Heat Island effect

UMT Urban Morphology Type

UNESCO United Nations Educational, Scientific and Cultural Organisation

Contents

1 Introduction

One of the main aims in the planning of cities should be to ensure a healthy living environment for the inhabitants. One important aspect of this is the human thermal comfort (HTC), which is the satisfaction humans perceive regarding the thermal conditions of their surroundings. This depends on a number of things such as the basal metabolic rate, clothing, degree of human activity, air temperature, wind, humidity and surface temperatures. The surface temperatures are the temperatures of surfaces close to the human body which directly affect thermal comfort by radiating heat towards the human body, for example an ice cold window pane in a warm room. As surface cover and materials found in cities are distinct from those in rural areas, the surface temperatures are also distinct. It has long been established that the altered surface energy exchange, which is described by the surface energy balance (SEB), has caused urban areas to experience higher surface temperatures than their rural surroundings (Eliasson, 2000, Spronken-Smith and Oke, 1998, Upmanis et al., 1998, Oke et al., 1991, Balchin and Pye, 1947), which in turn affects the air temperature in cities.

The air temperature in cities is of course also dependant on many other factors. Firstly, it depends on factors which cannot be directly altered except by choice of location, such as the local climate and weather, the surrounding topography and also the proximity to large open waters (Webb, 2016, Grimmond et al., 2010). The factors that can be directly influenced include the design of the city such as amount of green areas, which alters the SEB, and street layout, which alters the air movement and winds. They also include for example the use of cars and the amount of anthropogenic heat created, and choice of building materials. Factors directly affected by human agency, in turn, influence the factors such as the local weather factor mentioned above. This creates a cycle where cities both alter their own climate and are negatively affected by the change (Eliasson, 2000).

This altering of the SEB has been measured to result in air temperature differences of up to 12 °C, between urban and rural settings on calm and clear nights (Oke, 1981), while temperatures inside the urban context such as between parks and built up areas can vary by up to 7 °C (Spronken-Smith and Oke, 1998, Upmanis et al., 1998). The difference in temperature between urban and rural areas is larger at night, as this is when rural areas are cooled down by the radiation to the cool night sky, whereas in cities the buildings and streets release the heat that was stored during the day. The higher temperatures of urban environments affect human health and thermal comfort, leading in extreme cases to heat stroke, heat exhaustion, heat syncope and heat cramps (Arrau and Peña, 2015), especially when the body cannot regenerate during a cooler night.

The current climate change predictions of rising average temperatures by 1-2 °C, depending on climate change scenario (Wilby et al., 2004), are causing extreme concern and planners are struggling to deal with the changing climate. The two main strategies used internationally to handle global warming are mitigation and adaptation (Larsen et al., 2012). Mitigation is the reduction of emitted greenhouse gases (GHGs) that cause global warming, and adaptation is the dealing with climate change that is already happening or going to happen. Climate change adaptation is to a large extent about making cities resilient so that they are prepared for hazards or disasters that might happen in the near or distant future. The most common approach is to downscale global or regional climate change models from the IPCC and attempt to predict the future local climate (Webb, 2016). The predicted climate changes of average temperature are however, regardless of scenario, quite small compared to the mentioned changes that the construction of urban landscapes causes (Cavan et al., 2014). Thus, the knowledge of urban climatology could be an important help in the ongoing debate about climate change and the necessity of adaptation, especially when it comes to creating resilient cities (Schwarz et al., 2011, Webb, 2016, European Commision, 2013).

Some of the challenges of adapting to climate change are linked to the accuracy of projections, the unknown likelihood of predicted events to occur, the reality that the most vulnerable countries are also the poorest, and that the countries that have caused climate change are not paying for the adaptation (Füssel, 2007). In addition to this the pace of urbanisation is currently faster than the pace of economic and infrastructural development in many parts of the world, notably in areas of Africa, providing residents with few means to adapt to climate changes and extremes (Intergovernmental Panel on Climate Change, 2013). The fast pace of urbanisation threatens local ecosystems, which regulate the climate, as land cover composition and open green spaces are re-appropriated to accommodate growing populations. This combination of factors leaves areas most at risk with little option but to find 'low-key, no-regret' adaptation options, which increase resilience but are justifiable from economic, social and environmental perspectives whether natural hazards or climate change take place or not (UNDP, 2010, Dr. Siegel, 2015). As many African cities are currently devising plans to transfer unplanned informal areas into formal, planned housing districts, and knowledge and awareness around urban climatology is growing, the opportunity is there to integrate such 'low-key, no-regret' climate adaptation strategies into the emerging development plans.

Historically, the integration of urban climate knowledge into the work of urban planners has been difficult (Page, 1970, Oke, 1984, Bitan, 1988). Various methodologies, guidelines, tools and models have been developed (Oke, 1984, Bitan, 1988, Lindqvist and Mattsson, 1989, Givoni, 1991, Golany, 1996), however these have not been applied effectively (House-Peters and Chang, 2011). Climate change and other human activities complicate the exchange of energy at the surface, making it difficult to assign improvements in local climate to specific changes in the urban plan. Recently, however, a relation between land use and land cover (LULC) (Gill et al., 2008, Stewart and Oke, 2012) and land surface temperatures (LST) has been established (Grimmond et al., 2010, Cavan et al., 2014, Gill et al., 2008, Schwarz et al., 2011) and how LST varies spatially over LULC is well documented by using thermal infra-red measurements and airborne and satellite based instruments (Grimmond et al., 2010). This provides a means for connecting surface temperatures to human induced changes in land use, still required is a method for effectively integrating this into urban planning.

In Europe the EU is pushing for an integration of climate change issues into Strategic Environmental Assessment (SEA), which is a legally required and systematic environmental assessment tool for policies, plans and programmes (PPP) and as such well suited for tackling these issues

(European Commision, 2013). As this tool is achieving global status and has in recent years been introduced to Africa, it could potentially be used for integrating both local climatology and climate change adaptation issues into planning processes there. Adebayo (1991), who performed a thorough assessment of climate sensitive design in tropical Africa, notes that nearly all the internal and external factors that interfere with climate sensitive urban design in tropical Africa can be linked to politics. He reaches the conclusion that a way to solve problems identified with climate sensitive design in tropical Africa is for urban climatologists to pressure for building and planning legislations that include climate issues. This legislation could be in the form of SEA, where 'climatic factors' are to be included in the environmental report, which makes it a possible tool for implementing these legislations. However, assessments of performed SEA's show that these 'climatic factors' are most commonly interpreted as climate change mitigation or adaptation (Larsen et al., 2012, European Commision, 2013) and the extensive knowledge of urban climatology is not yet utilized (Schwarz et al., 2011).

This study aims to investigate the integration of urban climatology into climate change adaptation within the framework of SEA. Available urban climate models will be assessed and analysed to find a tool appropriate for integration into SEA by non-climate-experts. This study will not perform an SEA per se, but the framework of SEA will be borrowed for a case study testing the chosen urban climate model. This paper will also, through the results of the case study, attempt to provide some guidance to the Department of Urban and Rural Planning (DoURP), of Zanzibar regarding the possibilities of creating a more climate resilient city.

The outline of this report is as follows: section 2 will give an overview of the background and theory used in this report. The aim is described in more detail in section 3 which includes research questions and delimitations. Section 4 describes the methodology used for finding a suitable urban climate model that can be used in the framework of an SEA. This section also describes the methodology used in the case study. Section 5 presents the findings of the assessment of available urban climate models. The results of the comparison are summarised and the model deemed most suitable is presented. The case study is then described in section 6, including the introduction to the study area and the different steps of the framework of SEA conducted. In section 7 the results are discussed, first the assessment of the climate model, and then the results of the case study. The methodology and delimitations chosen are also discussed, as well as the use of the framework of SEA. Section 8 provides the conclusions that are drawn from this study and section 9 gives some guidance and recommendations to the urban planners involved in the new strategic action for the study area. Finally, section 10 provides recommendations for further studies and research.

2 Background

This chapter provides a brief overview of urban climatology and its basic theories, including different scales and indicators commonly used. It is followed by a discussion of the extent to which urban climatology has been integrated into urban planning historically. SEA is then presented as a tool for effectively handling the issues of integration and an overview is also provided for readers not familiar with the analysis tool. Finally, the issue of climate sensitive design in tropical Africa is introduced.

2.1 Urban Climatology

As mentioned in the introduction every human settlement has a unique climate shaped by its geographical location and its design (Webb, 2016). This is studied in the research field of Urban Climatology. The complex patterns of the urban climate are dependent on the parameters described in equation (1),

$$M_{i,t,x} = C_{i,t,x} + L_{i,t,x} + U_{i,t,x} \tag{1}$$

where $M_{i,t,x}$ is the measured or calculated value of a meteorological or air pollution parameter during weather situation 'i', at time 't', at place 'x' in the city; $C_{i,t,x}$ is the regional term, i. e. the large-scale weather situation and air pollution background load, $L_{i,t,x}$ is the local term, i.e. the climatic and air pollution effects due to topography and non-urban land uses and $U_{i,t,x}$ is the urban term, i.e. the climatic and air pollution effects of the construction of urban landscapes (Matzarakis et al., 1998).

The equation for the surface energy balance (SEB) mentioned in the introduction can be seen in equation (2) where Q* is the net all-wavelengths radiation, K the short-wavelengths or solar fluxes, L the long wave or terrestrial fluxes, and the arrows indicate whether the flow of energy is towards (↓) or away (↑) from the surface.

$$Q* = K * + L* = K \uparrow - K \downarrow + L \uparrow - L \downarrow \qquad (\mathrm{W\,m^{-2}}) \tag{2}$$

In the SEB it can roughly be said that all radiation that comes from the sun is either used for creating water vapour, turned into heat or stored in the earth. If vegetation or water at the surface is abundant, more of the incoming energy from the sun is used for vaporizing water (latent heat), if there is no water available to vaporize, more of the energy is turned into sensible heat, creating a hotter surface (House-Peters and Chang, 2011). So the latent heat flux Qe depends on the evapotranspiration E, see equation (3), where Lv is the latent heat vaporization of water (Arnfield, 2003). Evapotranspiration is a term that aggregates two phenomenon, evaporation and transpiration. The first is the evaporation of water present in building materials, soil or the atmosphere and constantly depends on availability of water and temperature. Transpiration is the evaporation of water from living plants and this varies to a larger degree as plants have the ability to control how much moisture is stored released.

$$Qe = LvE \qquad (\mathrm{W\,m^{-2}}) \tag{3}$$

Literature usually describes five ways in which the heterogeneous urban form and its building materials affects the different fluxes of the SEB (House-Peters and Chang, 2011, Masson, 2006)

1. Trapping of radiation in the urban canopy, i.e. between the buildings.

2. An uptake and storage of heat during the day due to thermal characteristics of building materials and the urban surface characteristics.

3. The generation of a positive heat flux at night from the city to the atmosphere when the stored heat is released from the buildings and other impervious surfaces.

4. Due to less vegetation a general favouring of sensible (heat) over latent (movement - water vapour) energy occurs.

5. A possibility of large anthropogenic heat fluxes in dense urban areas from burning fossil fuels, from cars or air-conditioning.

2.1.1 Differentiating Urban Scales

Differentiating spatial scale is very important for understanding urban climates, observations and modelling, see also figure 1. The different scales include building, street, neighbourhood and regional levels. The fluxes studied in the SEB need to fit the research context and have to be adapted to the different scales and the inputs chosen accordingly (Grimmond et al., 2010).

The street level, also called micro scale, takes place in the Urban Canopy Layer (UCL) which reaches from the ground up to the roof tops, see figure 1. Here inhabitants experience conditions such as sunny or shady streets, wind or a cool park. Important for this scale is the surface roughness length which describes how easy the wind moves through the setting. Also important is the fraction of the surface that is covered by impervious materials as this influences the evaporation. The sky view factor (SKV) is a measure of how exposed the city is to the open sky and how this affects the solar radiation reaching down between the buildings, how much radiation is trapped between the buildings and how much radiative cooling occurs at night through the cool night sky. Thermal admittance is the ability of building materials to store heat, and the albedo is their ability to reflect radiation. These two factors influence the heat stored in built structures and other man-made materials and surfaces. Anthropogenic heat fluxes can also play a large role.

The neighbourhood (local) scale is larger and less detailed and covers everything from several streets to small city districts. It is modelled in the near surface layer, see figure 1. Here land use and cover generate distinct local climates caused by the urban morphology, building materials, the amount of vegetation and human activities such as released heat or water (Grimmond et al., 2010).

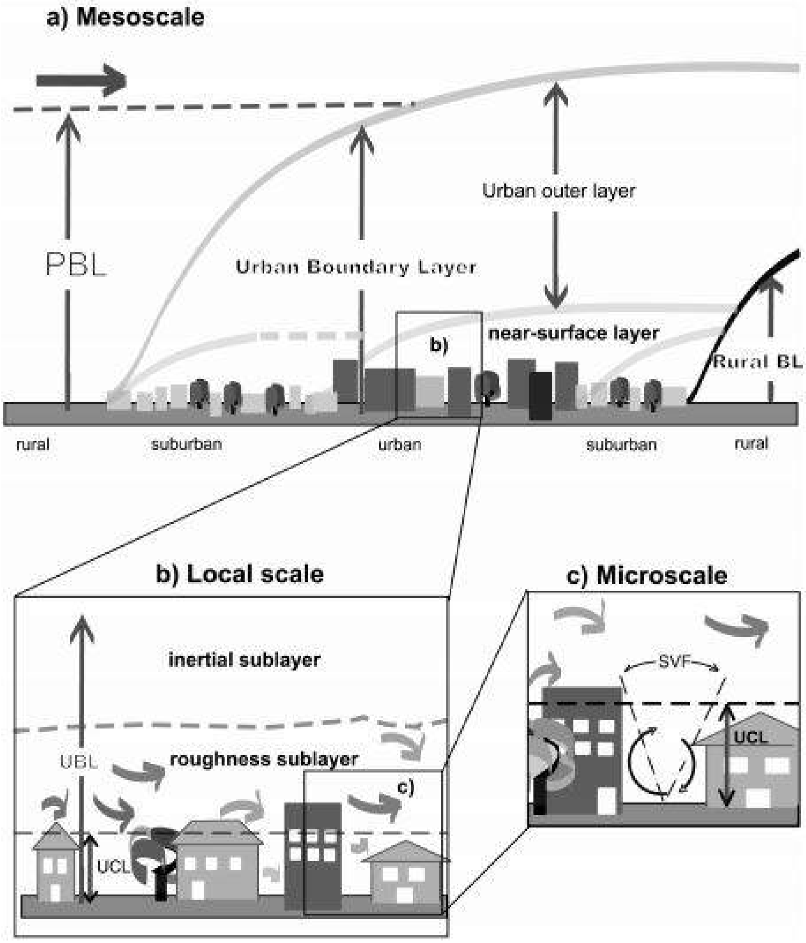

FIGURE 1: This schematic diagram shows the different processes, flows and scale lengths of the urban boundary layer, UBL, within the context of the planetary boundary layer, PBL, the urban canopy layer, UCL, and the sky view factor, SVF, by B. Fisher, J. Kukkonen, M. Piringer, M. W. Rotach, M. Schatzmann, 2006

The building and regional scales, even though sometimes touched on in this study, are not appropriate scales for SEA and therefore not described here in great detail. Building scale handles issues in and around single buildings, and the regional scale or mesoscale describes whole cities or regions.

2.1.2 Indicators

Variables that affect HTC and that can be influenced by city design are air temperature, wind, humidity and surface temperatures. The indicator most commonly used for measuring HTC is air temperature. This has many reasons such as the large impact of the exchange between the human body and the surrounding air on thermal comfort, and because of the long established methods of measuring air temperature, such as thermocouples and thermistors (Grimmond et al., 2010). There are however some drawbacks to using air temperature as an indicator in the context of urban planning. For example no simple model can be created that effectively describes how land use and air temperatures correlate, as they depend on many other variables such as humidity, radiation, wind, rain and the temperatures of surfaces close by (Brown and Gillespie, 1995). Surface temperatures on the other hand are directly related to the surface and its land use through the SEB and can therefore be modelled explicitly (Gill et al., 2008). Mean radiant temperature (MRT), which is the combined radiative effect of all surface temperatures within a space (Matzarakis et al., 1999, Thomsen et al., 2008), is therefore a good choice of indicator in the context of urban planning (Matzarakis et al., 1999, Gill et al., 2008). In the context of land use the term MRT is often replaced by the more readily understandable term land surface temperature (LST).

2.1.3 Classifying Land Use and Land Cover

In order to effectively couple the LST to different land uses, land cover and future changes in land use, an appropriate classification of these is needed. Historically, the classifications of urban and rural have been used to describe temperature differences of the urban heat island effect (UHI) (Stewart and Oke, 2012), which is the observed temperature difference between urban and rural settings. However, this approach poses limitations, even in the context for which it was developed, as the possibilities of comparing research between study cases remains unstandardised and inaccurate. Airports have for example been both classified as urban and as rural (Eliasson, 2000), and temperatures within the urban context can vary considerably as stated in the introduction (Spronken-Smith and Oke, 1998, Upmanis et al., 1998). For a universal comparison of urban temperatures a universal classification of LULC is needed (Stewart and Oke, 2012). Two recent approaches for improved classification include Local Climate Zones (LCZ) developed by Stewart and Oke (2012) and Urban Morphology Type (UMT) developed by Gill et al. (2008).

The LCZ approach uses a set of defined areas that have been designed to fit all study areas globally. The different classes come with pre-defined properties and areas defined should have a minimum of 400-1000 m diameter. The UMT approach was originally developed for Manchester, UK, and can be adapted to various contexts. The areas should be between 0.04-5 km^2 (or 4-500ha) and properties need to be defined manually for each type, such as surface cover composition and average building mass.

2.1.4 Climate Change Adaptation

Recently, climate issues in cities are receiving rapidly increasing attention, not due to urban climatology itself but because of climate change and the necessity of adapting cities to it (Webb, 2016). The two main strategies, climate change adaptation and mitigation, used to tackle these issues, are two complementary approaches. Difficulties with climate change adaptation as opposed to mitigation include monitoring effectiveness and dependence on the accuracy of climate change projections (Füssel, 2007). Further the polluter-pays principle does not apply as most adaptation is necessary in developing countries of which most have not contributed significantly to greenhouses gas emissions. Also adaptation is only possible in certain climate-sensitive systems as for example cities. How would one adapt a Pacific coral atoll? On the other hand adaptation is necessary due to the large effects even small climate changes have (Rosenzweig et al., 2007) and the already accumulated emissions of GHGs. Adaptation, unlike mitigation, is possible at a local or regional scale, doesn't depend as much on the actions of others and may have important ancillary effects (Füssel, 2007). The two approaches are complementary and their time-scales and actors are largely distinct. It is important that they are integrated into each other, as they could otherwise work against each other, for example in the case of installing fossil driven air-conditioning, which could help adapt a city to a changing climate, but would release precisely those gases trying to be mitigated.

The IPCC defines an adaptation assessment as ”identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, efficiency and feasibility” (McCarthy et al., 2007). Two complimentary approaches common in guidelines are the hazards-based approach and the vulnerability-based approach. The former is initiated by modelling climate change projections, non-climatic factors are usually not considered (UNCCD, 2009). These assessments have been crucial for identifying risks of climate change but their results have not been extremely useful for policy adaptation design. Limitations include their strong reliance on model-based climate and impact projections, which may not be available at a relevant spatial scale or time frame.

The latter, vulnerability based approach, assesses future climate change in the context of current climate risks (UNDP, 2012). A strong focus is on social factors that determine the ability to cope with climatic hazards. This approach links past experiences of climate change risk directly to the present activities of stakeholders. Some useful results have been produced by this method even in the absence of reliable impact projections, for example options that are robust against a wide range of plausible climate developments. This approach comes with a greater reliance on expert judgement, limited comparability across regions and the lack of clear methodology. It includes the ’no-regrets’ solutions mentioned in the introduction.

2.2 Climate Consideration in Urban Planning

One of the earliest references of considering climate in urban design is found in Roman architect Vitruvius "The ten books on Architecture", that date back more than 2000 years, and discuss the layout of towns and buildings depending on various influences of the climate. Traditional and indigenous buildings and built up areas all over the world were also adapted to and organised around different climates (Eliasson, 2000). Nowadays six key factors are often described that can typically be influenced by planning departments and which influence the urban climate; the level of urban density, street orientation, street aspect ratio, neighbourhood and building typology, size, type and location of city parks, and paving and building materials (Erell, 2008). Urban density and paving and building materials have an important effect on how much heat is stored in the buildings during the day and released during the night. Street orientation, street aspect ratio and neighbourhood and building typology have an impact on the air flow and wind speed in a city which is very important for pollution and perceived air temperatures. The street aspect ratio, ie the ratio between the width of streets and the height of buildings, also affects the incoming radiation which in turn also affects the actual and perceived air temperatures. Size, type and location of city parks have numerous influences on the urban climate, which implies that involving landscape architecture in settlement planning plays an important role (Bitan, 1988). Rows of trees produce windbreaks, deciduous trees provide shaded areas in summer, grass areas minimise absorption of solar radiation and water elements such as fountains and artificial lakes raise humidity and reduce temperatures.

Publications on urban climatology started when the traditional building became an industrial one in the 1900's, and the energy crisis in the 1970's further pushed an integration of climatology knowledge into urban design. Even though the field is well documented to date actual impact on everyday life has remained low (Eliasson, 2000). This could, in part, be due to the fact that until the debate about global warming started the urban climate was only one of many issues to be considered in urban planning. Oke (1984) wrote in 1984 that the lack of application can mainly be brought down to communication problems regarding the separate needs of urban planners and urban climatologists. He further states that the most positive results of integration are seen where extreme weather conditions prevail, and in cases where legislated planning requirements apply and proven applied methodologies exist. These issues have until now mainly included air pollution and precipitation run-off, but also in certain cases wind or solar radiation. In 1988, Bitan wrote that to improve how local climate is affected by the built environment, it needs to be integrated into all aspects of planning, reaching from regional planning, land use planning and detailed planning of industrial, commercial and residential zones, to the design of single buildings. He also presented a methodology for implementing this. Still in 1996 Eliasson writes how the actual influence on plans remains low, and Goldberg et al. (2013) states in 2013 that it has seen a slow increase in recent decades.

With global warming increasingly to the fore on the global agenda the issue of integrating urban climatology into urban planning is more pressing than ever. Knowledge of climate change has mainly been built on macro-climatic modelling and the downscaling of these to the urban context (Webb, 2016), which is far from simple and presents many uncertainties (Wilby et al., 2004).

A lack of approaches making use of urban climatology is prevalent (Webb, 2016), even though Matzarakis et al. already in 1998 described how urban climatology could be adapted to include climate change issues by adding a term $G_{i,t,x}$ to equation (1) seen above, which represents the urban term induced by global change, i.e. the climatic and air pollution effects of global change effects, see equation (4).

$$M_{i,t,x} = C_{i,t,x} + L_{i,t,x} + U_{i,t,x} + G_{i,t,x} \tag{4}$$

There can be large benefits to climate change adaptation strategies if they consider the factors of urban climatology (Webb, 2016). In a few cases, where a long ongoing collaboration between urban planners and local climate researchers existed, very positive results have been achieved regarding resilient cities. A good example is seen in the city of Stuttgart, Germany. Its climate change strategy of 2010 built strongly on the expertise of the long established in-house climate unit, whose administrative status and application of research was formalised already in 1953, mainly because of problems with air pollution (Webb, 2016). The city has also published an environmental design guide, the 'Climate Booklet for Urban Development' using a mix of spatial and sectoral instruments and providing recommendations regarding issues such as fresh-air ventilation, mitigation of air-pollutants and greenhouse gases, open space provision, tree-planting and façade and roof greenery. The most distinctive contribution from the city of Stuttgart however, is the instrument 'Klimaatlas', a spatial document that combined weather observations, atmospheric modelling, three-dimensional mapping and GIS data. By mapping the physical structure of the urban climate, site-specific policy recommendations can be derived and small-scale interventions can be developed, rather than solely relying on the downscaling of regional climatological data which can lead to quite indistinct standard strategies.

In Summary, climate change adaptation strategies can potentially benefit greatly from the field of urban climatology providing its integration into urban planning is managed carefully. It is essential that a coherent methodology is developed in order to effectively integrate urban climatology into urban planning and with it climate change adaptation if any of the stakeholders are to benefit from it in the long term.

2.3 Strategic Environmental Assessment

Strategic Environmental Assessment is a tool that integrates sustainability issues into decision making at an early stage, aiming to protect the environment and promote sustainability (Therivel, 2013). The modern concept of SEA has received international recognition, is institutionalised in whole regions and has been adopted by international organisations to strengthen development planning (Posas, 2011). In developing countries SEA is mainly practised in association with development bank requirements, whereas in developed countries it is more systematically practised and often in connection to formal requirements from Environmental Impact Assessment (EIA) law or for example the EU SEA Directive.

The ultimate aim of an SEA is to protect the environment and promote sustainability (Therivel, 2013) and its main strength lies in considering the environmental consequences of strategic actions before a development alternative is chosen. It can help to find the best strategic action available by identifying different possibilities of meeting the needs of the decision maker. This could for example include options that meet the demand present whilst minimising the damage, but it could also imply modifying the demand rather than accommodating it. Therefore it is important that the decision-maker is active in the SEA process so that the findings are taken into account when the decision is made. Other stakeholders such as the public should also be involved to extend the views of the decision maker to include other aspects than the main area of interest.

The SEA process can systematically strengthen the treatment of climate change in planning and development due to its practical, analytical component, its focus on participation and its ability to handle ethical issues and reconcile competing agendas. The broad variety of regions and strategic actions where SEAs can be applied indicate that the environmental and sustainability constraints should adapt to these and reach a level where only key constraints are in focus. It should not be as detailed as a project based Environmental Impact Assessment (EIA) nor does it need to create a huge collection of baseline information that is not directly relevant to the key constraints. The precautionary principle should be applied, meaning that the SEA needs to ensure that limits beyond which damage is irreversible should be identified and not exceeded. As this requires some amount of human judgement it can be stated that SEA is not a truly scientific instrument.

The procedure of an SEA can broadly be divided into five steps (Therivel, 2013):

- Scoping - Set the institutional structure: get the timing right, determine who should be involved in the SEA and how it fits with other assessment requirements.
- Baseline - Describe the context: identify constraints and objectives set out by other strategic actions, describe the current and likely near future baseline environment without the assessed interventions, and identify environmental problems.
- Alternatives - Clarify the strategic action's objectives, and identify sustainable options for achieving this objective.

- Assessment - Identify, assess and evaluate the likely environmental impacts of the options, choose the preferred options(s), mitigate significant negative impacts.
- Evaluation and follow up - Document the process and monitor the impacts.

SEA has recently found its way to Zanzibar where it is being studied and taught at the State University of Zanzibar (SUZA), and it has also been introduced to some political departments such as the Department of Environment and the Zanzibar Environmental Authority. However it has not as yet been used to assess any policies or plans, whereas EIA is quite widespread.

2.4 Climate Sensitive Design in Tropical Africa

In the rapidly urbanising tropical Africa that is facing climate changes of between 1-2°C (IPCC, 2007), urban local temperatures are becoming increasingly important to consider and actively include in planning and policy. In general the climatological precautions that need to be taken include aversion to urban floods from the intense and extremely heavy rains, and cooling and ventilation all year round (Webb, 2016).

Oguntoyinbo's (1986) review of contributions to urban climatology in tropical Africa shows that little is known about the nature of urban climates in the study area. In tropical regions inhabitants may be negatively affected by urban warmth during the whole year due to the lack of a cold season (Grimmond et al., 2010). The tropical climate experiences larger diurnal differences in temperature than seasonal (Adebayo, 1991), and the seasons alternate between wet and dry. Here ventilation is critical so street geometry needs to be designed to increase air flow and provide shade.

According to Bitan (1988) open and better-ventilated settlement patterns are recommended. The high angle of the sun calls for a combination of building heights, geometry and elements like canopies, awnings and vegetation (Grimmond et al., 2010). The high angle also implies that roofs are the most important thermal building surface. Vegetation is often abundant in tropical regions due to humidity and rain seasons and it can be used for evaporative cooling and providing shade (Grimmond et al., 2010). Green roofs or roof top gardens can insulate buildings, improve air quality, reduce storm water run off intensity, improve the quality of run-off water and increase biodiversity.

Building and urban design in tropical Africa has in the past seen an unfortunate mix of external influences that do not take into account local conditions, uncontrolled urbanisation, an unstable political environment and a lack of research on local urban climates (Adebayo, 1991). The DoURP, part of the Department of Lands, under The Revolutionary Government of Zanzibar, is showing a stark contrast to this as they are currently devising a new development plan for the study area. They are trying to guide the development into a new direction without losing the peoples important local heritage along the way.

3 Aim

The aim of this report is to assess how urban temperatures can be affected by changes in land use. These changes could stem from urban planning, or from the informal spreading of settlements. This study aims to find an urban climate model that can integrate urban climate issues into land use planning at an early stage. The study mainly considers the issues and needs faced in developing countries, more specifically tropical eastern Africa. It also attempts to show that the use of urban climatology in climate change adaptation can be a successful strategy.

In addition the study aims to test the STAR tool model for urban climate modelling in the tropical urban context of a developing country, for both baseline and future temperatures. It will be investigated how the modelled temperatures depend on both climate change and changes in land use.

The study also aims to assess if this developed methodology, including model and framework, is suitable for use in the context of a developing country, and if it can be useful for local urban planning departments. The framework of SEA is used in order to provide a hint as to whether the methodology of urban climate modelling used in this approach, could be used within complete SEAs in the future.

3.1 Research Questions

The following research questions will be answered:

1. Which urban climate model is well equipped for use in an early urban planning phase, for issues of climate change adaptation, in the context of developing countries?

2. Can the use of this model, when used for assessing low-key, no-regret climate change adaptation strategies, fit in the framework of SEA?

3. What measures could the DoURP of Zanzibar integrate into their urban spatial strategy, that are socially, economically, and environmentally feasible, whether climate change occurs or not, to ensure a future climate resilient Zanzibar City?

3.2 Delimitations

This study is limited to the local context of the case study, which is the tropical climate of the developing country Tanzania. It only considers climate change adaptation, not mitigation, and is limited to the indicator of surface temperatures for assessing human thermal comfort. Other factors, which may influence human thermal comfort have not been directly considered. Nor have other factors of climate change adaptation, such as surface water run-off.

The research of this report focuses on the comprehensive planning level, and how this can affect urban temperatures. It does not include possible positive or negative synergies between different issues in climate change or urban planning. The study does not verify the results of the modelling and it does not follow up and evaluate how changes in land use actually affected the surface temperatures.

4 Method

In this chapter the methodologies that were used are described. In section 4.1 it is described how some available urban climatology models were assessed in order to choose a suitable one. Section 4.2 describes how the chosen model was used for a case study on Zanzibar.

4.1 Assessment of Available Urban Climate Models

A thorough study of relevant literature was performed in order to evaluate different modelling methods and available climate models. After reaching the conclusion that the SEB and surface flux models were best suited to the context, freely available alternatives were located. It was attempted to download the free software and to read the user manual. Models that required a large amount of input data that was not available were not tested. Models that required a large amount of time to understand and start using were deemed unsuitable. Also models that required special software not freely available, or any sort of programming skills were abandoned. This is due to the fact that it was deemed essential that the chosen model should be available anywhere for anyone, to be used by urban planners and climatological non-experts alike. The user-interface was assessed for a user-friendly and intuitive design. Finally the form of output was compared for ease of use for further work and documentation. The researcher chose one to continue with for the case study, and the choice was based on the following criteria: Availability, accessibility, input parameter requirements, ease of use for non-experts including complexity and user-interface, time requirements, and finally the usability of output.

4.2 Methodology of the Case Study

The theory of urban climatology was used to integrate climate change adaptation into an urban planning procedure in the western urban district of Zanzibar City. The framework of SEA was borrowed, and the urban climatology model chosen in section 5 was used for the assessment.

4.2.1 Scoping

In the scoping phase it was determined whether an assessment of the urban climate is needed, which factors should be included and which stakeholders should be involved. Different departments of the Revolutionary Government of Zanzibar were visited such as the Department of Environment, the Department of Forestry and the Department of Water. During conversations with the heads of each department important environmental issues and regulations were assessed and documented and a general overview over the situation was established. The director of the DoURP Muhammad Juma voiced his interests and these were compared to the opinions of the other directors. An expressed concern about climate change and creating a resilient city confirmed the undertaking of this study.

4.2.2 Baseline

The baseline was described by conducting thorough field studies in the area. These were performed during December 2015 to February 2016 and included mapping each house in the area, i.e. visiting the different neighbourhoods with a dated map and updating it. The building typology and materials and also architectural style for each house was assessed and documented in Open Source Mapping. This was performed in collaboration with the DoURP and the Dutch architecture consultancy firm African Architecture Matters and is part of an ongoing planning project of the area. The results of this assessment were also used for a workshop in Amsterdam in February 2016, and will be used for the development of the new land use plans for the study area.

Some time was spent in the Zanzibar City archives and DoURP library finding other strategic actions and regulations that could have an influence on the 'SEA' or the new strategic action.

The digitising of current land use and temperatures followed the methodology described in section 4.2.4.

4.2.3 Alternatives

For the future scenarios of the land use, the DoURP's first sketches of the new development plan for the area were used as a basis. The scenarios were modelled for when the land use transition was completed and not during any development stages. Several planning alternatives were prepared considering both the visions of the department, environmental issues and the opinion of the public. In these, the future spatial distribution of LULCs did not change within the planning alternatives. Rather, the surface compositions within the LULC were altered. This means that for example the land use category 'Education', the location of schools did not change in the different planning alternatives. What changed was the surface composition, such as the percentage building cover, paved area and grass. This provides the means for urban planners to, in a simple way while designing a regular plan, account for climate change adaptation simply by changing the regulations of what different land use classes should include. For example the maximum density in residential areas, or the amount of trees to be planted in governmental areas.

The different surface compositions of alternatives include a best case scenario, a worst case scenario, and several alternatives regarding density in the traditional residential areas. The best case scenario included an increase in evaporative surface cover by 20%, in all land uses that had a baseline evaporative surface cover under 50%. In the worst-case scenario the vegetation in all land use categories was drastically reduced by 50%. For the different densities of the residential areas two approaches were used, first the freed-up land was converted into equal shares of 'impervious surfaces', 'evaporative surfaces' and 'bare soil or sand'. Then the same scenarios were modelled again but this time all freed-up land was converted into 'evaporative surfaces' and the difference was assessed.

4.2.4 Assessment

In order to digitise and map the baseline and evaluate the different planning alternatives an LULC classification system was first needed. The UMT system was chosen and a manual classification of UMT types was performed. First the spatial distribution of the different UMT categories was assessed. For the baseline this was based mainly on the field studies whereas for the alternatives the new land use plan designed by the DoURP was used. A grid based approach in ArcGIS was used, where a 30 x 30 meter grid was drawn over an high resolution orthophoto of the study area. Each grid cell was manually clicked and the fitting UMT category was entered as an attribute. The UMT classes are based on Cavan et al.'s (2014) adaptation of Gill et al. (2008) and have been further adapted to the context of Zanzibar City as following:

- Non built-up areas
  - Beach
  - Bushland
  - Cemeteries
  - Mixed forest
  - Mangrove
  - Marsh/swamp
  - Parks
  - Sports ground
  - Other open space
- Transport
  - Bus terminal
  - Major roads
  - Other impervious areas

- Built-up areas
  - Traditional residential
  - Modern housing low-rise (1-3 storeys)
  - Modern housing mid-rise (4-9 storeys)
  - Modern housing high-rise (9+ storeys - non-existent)
  - School
  - Religion
  - Governments
  - Market

Examples of the chosen UMT categories can be seen in figure 2, starting from top left they include 'Traditional Residential', 'Park', 'Modern Mid-rise', 'Open Water', 'Major Roads', and 'Government'.

FIGURE 2: Some of the UMT categories used, starting from top left they include 'Traditional Residential', 'Park', 'Modern Mid-rise', 'Open Water', 'Major Roads', and 'Government'. Top-left and bottom-centre pictures by Mia Callenberg. Top-right picture by Peter Meller, remaining pictures by author.

For the baseline the surface composition of each UMT category was divided into the categories 'Built-up area', 'Road', 'Impervious', 'Vegetation & water', and 'Bare soil & gravel'. The surface cover of each UMT was assessed during the field studies and also added as an attribute to each grid cell in ArcGIS. For example the UMT category 'School' was estimated to have a surface cover composition of 10% 'built-up area', 20% 'impervious', 10% 'bare soil & gravel' and 60% 'vegetation & water'. Note that this is unique for each single UMT category. The surface composition assessment has in earlier studies (Cavan et al., 2014, Gill et al., 2008) often been done through a random sample point approach, where a certain amount of randomly selected points from each UMT category are analysed and seen as representative for their UMT. However due to the rather small size of the studied area and the detailed field studies, the assessment of the surface composition has been done manually. As input several sources were used including a high-resolution orthophoto, Google Earth, Open Source Mapping (OSM) and personal observations during field studies.

For the different planning options the surface cover composition was changed, for example in the worst case scenario the UMT 'school' is predicted to have a composition of 10% 'built-up area', 35% 'impervious', 25% 'bare soil & gravel' and 30% 'vegetation & water'. The spatial distribution, i.e. the location of the schools did not change.

After the assessment of the LULC the surface temperatures needed to be assessed. The model chosen for this study is the STAR tool, an energy balance model freely available on-line developed by Gill et al. (2008), see description in section 5. This model was used to assess the surface temperature for the different UMT categories, and also for the different surface cover alternatives.

The first inputs required are the study areas. Each UMT category was entered as a separate study area so that distinct surface temperatures would be modelled per category. Distinct input parameters for the UMT categories were the surface composition which was entered in percent per surface cover, and the average building mass per m^2 which depended on whether buildings in the UMT were estimated to be traditional or modern. The building masses were calculated differently depending on the building materials used. Other inputs were the same for all UMT types and include: base line air temperatures for the period 1961-2000, 2050's high temperature, density of air, latent heat of evaporation, soil type, air temperature at the surface boundary level, soil temperature, sunrise and sunset time, specific heat of air, specific heat of soil, density of soil, specific heat of concrete, major road mass, impervious surface mass, roughness length, height of surface boundary layer, wind velocity at surface boundary layer, specific humidity at surface boundary layer, peak insulation and night radiation.

The default output of the STAR tool model is the maximum surface temperature, i.e. the hottest temperature of a surface that could be expected during the day. This is averaged over the different surfaces in each UMT category. Three future temperature scenarios are possible; 10 % probability - very unlikely to be less than, 50% probability - central estimate, as likely as not, and 90% probability - very unlikely to be greater than, and for this study the 50% probability central estimate will be used. The model uses a British climate projection model for climate change projections, and this is based on the IPCC climate change scenario SRES A1FI which is the high emissions scenario. Note that current emissions are projected much higher than the highest emission scenario (Gill et al., 2008).

The outputs were exported to Excel where the data was sorted and placed into tables. The data was used for creating charts and diagrams. The modelled temperatures and evaporative fractions were also assigned as attributes to the UMT grid cells in ArcGIS to create temperature maps.

5 Assessment of Available Climate Models

Available models for urban climatology can be broadly grouped into empirical methods, physical (scale) models and numerical models (Oke, 1984). There are many options available to generate high spatial resolution climate information (IPCC, 2004), including Surface Energy Balance (SEB) models, surface-flux models, downscaling climate change models and remote sensing. They vary greatly in scale, variables accounted for, amount of input information and detail of output however they are often quite complex and/or computationally expensive.

SEB models have been a research goal for the international community of urban climatology so that the UHI could be better represented in weather prediction (Hidalgo et al., 2008). They usually follow one of three approaches, 1. models statistically fitted to observations, 2. modification of models designed for rural, vegetated areas, and 3. the development of new models specifically for urban areas. The first approach includes all models based on statistical algorithms, parameterisations, engineering formulae and qualitative conceptualisations (Oke, 1984). They are linked to observations of the SEB that are collected during field campaigns conducted in urban areas. The main asset of these models is their simplicity, as they need few inputs (type of surface, incoming solar radiation) and computation is very efficient (Hidalgo et al., 2008). Their dependence on actual observed input is both a strength and a weakness, as they build on real world conditions but are only valid for a specific location or situation (Oke, 1984). One of the most well-known and accurate models is LUMPS.

The second approach, the modification of models designed for rural, vegetated areas, uses the extensive empirical research conducted into soil-vegetation-atmosphere-transfer (SVAT) models and adapts these to the urban context. The basic idea is that surface radiant temperature (Tir) and with it the turbulent energy fluxes are dependent on the surface soil water content, and the fluxes are derived through the SVAT (Carlson and Arthur, 2000). Among the main parameters to be modified are the increase of surface drag from the presence of numerous large obstacles, the reduction of water available at the surface, the increase of heat storage in the surface materials, the trapping of radiation inside the canyon shape of the streets and the additional releases of heat by human activities (Hidalgo et al., 2008).

The holistic aim of the third approach that develops new models dedicated to urban areas, involves accurate conceptualisations of the urban surface. These models are based on general and realistic equations and require more computational resources. Numerical models include all mathematical equations that are linked to analytical techniques to reproduce the urban climate. If these models are validated against field data they hold great potential for predicting urban effects (Oke, 1984). As they require detailed input data they are more suitable for smaller scale planning and for use by climate experts.

As the prospective users of the model will be urban planners or non-experts working in municipalities etc, and there is no abundance of financial or computational resources, the models that build on statistically fitted observations are deemed most appropriate. These, as stated, require minimum input values and computational resources. The problem that they are very site-specific will be dealt with by adapting the input values to the current research area. As the output is used for guidance, understanding and the development of low key no regret adaptation options this should be an appropriate method as it does not require the modelling to produce 100% accurate results with a known uncertainty value. If the outputs would be used for specific, high-cost adaptation measures more security and certainty would be required in the modelling process. A comparison of some of these models is presented in table 1 below. One model was assessed to be more suitable than the others and was chosen to continue with for the case study, this choice was based on the following criteria: Availability, accessibility, input parameter requirements, ease of use for non-experts including complexity and user-interface, time requirements, and finally the usability of output.

Table 1: A comparison of the attributes of the urban climate models studied in this report, based on (London Urban Meteorological Observatory, 2016). The common denominator of the models is that they are based on a statistical fitting to actual observations, which makes them reasonably accurate with comparably few inputs.

Name	LUMPS	LUCY	STAR	FRAISE	Greater-QF	SUEWS	ENVI-met
Complexity	Simple	Simple	Simple	Simplest	Simple	More complex	More complex
Software provided	Windows exe	Windows GUI	Internet Browser	R code	Windows GUI	Fortran	Object Pascal
Applicable period	Hourly	Hourly - annual	Daily max mean temperature	Midday within 3 h of solar noon	30 min - annual	5 min - annual	Defined by user
Unique features	Radiation and energy balances	Anthropogenic heat flux only	Surface temperature and water run off	Active surface fluxes	Anthropogenic heat flux for London	Radiation, energy and water balance includes LUMPS	Computational Fluid Dynamics
Access	Freely available upon request	Freely available upon request	Freely available without download	Freely available upon request	Freely available upon request	Freely available upon request	Basic version is freely available
User Interface	Difficult	Easy	Easy	Moderate	Moderate	Difficult	Moderate
Adaptable to different contexts	Yes	Yes	Yes, default input data only provided for UK	Partly, requires leaf-on, leaf-off seasons	Only available for the area of London	Yes	Yes
Input parameters	Complex	Simple	Moderate	Simple	Moderate	Complex	Complex
Scale	Micro to local	Local to global	Local	Local	Local	Local	Building to Micro
Approach	Surface Flux Model	Energy Balance Equation	Surface Energy Balance Model	Surface Flux Model	Anthropogenic heat flux model	Evaporation-interception approach	Computational Fluid Dynamics

Variables affecting surface temperature are well known but the influence of these on micro scale variations is not so clearly understood (Grimmond et al., 2010). In the context of Zanzibar measured data is scarce and alternatives are needed. In the context of SEA the method used needs to be able to be performed by non-experts, have a reasonable amount of and readily available input data, and the output data needs to be relevant for planning purposes. Most importantly in SEA it is necessary to predict future temperature changes for several planning alternatives.

According to the criteria the STAR tool model is chosen, as it is the most user-friendly, requires minimum computation resources and a minimum amount of measured input parameters. More advanced input parameters, such as surface cover composition, can be estimated by local experts. A drawback is that it is on-line and the user needs a functioning Internet connection during the calculations. No download of software however is necessary, and the calculations are fast. The program also has a smart memory and will remember work that is entered. The

Parameter	Value	Unit
Reference temperature 1961-1990	31.29	C
Reference temperature 2050s	32.41	C
Sunrise time	600	h
Sunset time	1800	h
Specific heat of air	1006	J/kg/C
Soil depth	20	cm
Thermal conductivity of soil	1.083	W/m/C
Specific heat of soil	1180	J/kg/C
Density of soil	1800	kg/m3
Specific heat of concrete	880	K/kg/C
Building mass Modern building	1180 + 825 per extra storey	kg/m3
Building mass Swahili house	650 + 620 per extra storey	kg/m3
Major road mass	362	kg/m2
Other impervious surfaces mass	292	kg/m2
Roughness length	2	m
Height of surface boundary layer	1468	m
Wind velocity at surface boundary layer	5	m/s
Specific humidity at surface boundary layer	0.002	
Peak insolation	1050	W/m2
Night radiation	-148.7	W/m2

FIGURE 3: Input parameters used for the STAR tool model. Inputs adapted from (Cavan et al., 2014) and STAR tool model developed by (Gill et al., 2008)

output is the surface temperature for different climate change scenarios and can easily be exported to Excel or any other spread sheet program.

The original model by Tso et al (1990) was further developed by Whitford et al (2001) and has recently been developed into a freely available web tool by The Mersey Forest and The University of Manchester (2011) (Cavan et al., 2014). It is a surface temperature model based on the surface energy balance equation. Input parameters include the daily mean maximum temperatures of 98th percentile, ie the maximum mean daily temperature that can occur twice a year, the average building and road mass per m^2, the surface cover composition etc, see also figure 3 below:

6 Case Study

The case study is based on Zanzibar, Tanzania and attempts to test the urban climate model STAR tool in the framework of SEA. The model will be tested on a strategic action currently being developed, which is the new land use plan of the 238 ha large study area. The output of the modelling will be used to develop planning alternatives that ensure a future climate resilient city. The study aims to achieve this mainly through low-key, no-regret adaptation measures that are socially, economically and environmentally sustainable whether climate hazards occur or not.

6.1 Introduction to the Study Area

Zanzibar, the archipelago off the coast of Tanzania, consists of the two larger Islands Unguja and Pemba, and several smaller ones (Gossling, 2001). It became independent when the sultan of Oman was overthrown in the revolution of 1964 (Gillespie and Clague, 2009), after which an Act of Union with Tanganyika was signed. Together they became the United Republic of Tanzania while Zanzibar still has a separate legal system and shares only the Court of Appeal with Tanzania. The Archipelago is also entitled to all its earnings from foreign exchange and so it is partly economically independent as well.

There is one large city on Zanzibar and it lies on the west coast of the island Unguja, a three hour boat ride from Dar es Salaam. It consists of the UNESCO world heritage site Stone Town, and Ng'ambo, which means 'the other side' in Swahili. The two used to be divided by a large creek that cut through the area from north to south, hence the name 'the other side'. The creek has now been filled up and turned into a road, 'Creek road'. Stone town is an old Arabic town, which developed as a result of the old trade routes across the Indian ocean, between Africa's eastern coast, India and the Arabian peninsula. Its high, whitewashed buildings with ornamental doors and narrow curved streets stand as a stark contrast to the area on the other side of Creek road. Ng'ambo is a dense residential area, mainly made up of traditional African housing, and it follows no strict urban plan.

In modern times several architecturally brutal attempts of 'tidying' up the different districts of Ng'ambo have been made, by Dutton in the 1940's, by Karume and communist East German planners in the 1970's and by Chinese planners in 1982. The present ongoing attempt is based on a thorough assessment of the area made by a consultancy firm and sponsored by the World Bank; Zanplan (Government of Zanzibar, 2014). The assessment resulted in several 'Action Plans', which the different political departments of The Revolutionary Government of Zanzibar are expected to more or less follow. The 238 ha large area just outside of Stone Town, divided into quarters by Karume's massive road project, is the study area of this case study, see figure 4. It is bordered by Creek road in the west, the ocean in the north and south, and to the east the border follows one of the main roads going in a north-south direction through the area, Felix Moumie road. It consists of 49% residential areas, 19% economic buildings, 17% public space, 8% public services and 7% open space (Government of Zanzibar, 2014), and is home to approximately 33 thousand people.

Figure 4: The study area covering 238ha, part of Ng'ambo, Zanzibar Town. It is bordered by Creek road in the west and Felix Moumie road in the east. The blue star on the map indicates the position of the house discussed in section 6.1.1 and figure 8.

The Department of Urban and Rural Planning that is responsible for the development of the area is collaborating with the Dutch consultancy firm African Architecture Matters. The Department and the Consultancy firm are jointly undertaking a thorough 'mapping' of the study area, where a detailed map of the residential area is being created, and the different architectural typologies and building materials documented. Several workshops have been held, whereof one in Amsterdam that attempted to 'map' the intangible qualities of the area, and one in Ng'ambo that aimed to involve the public and create a dialogue with the inhabitants of the area. Both studies have contributed to the development of a new land use plan, the first sketches of which form the basis of this case study, see also figure 5.

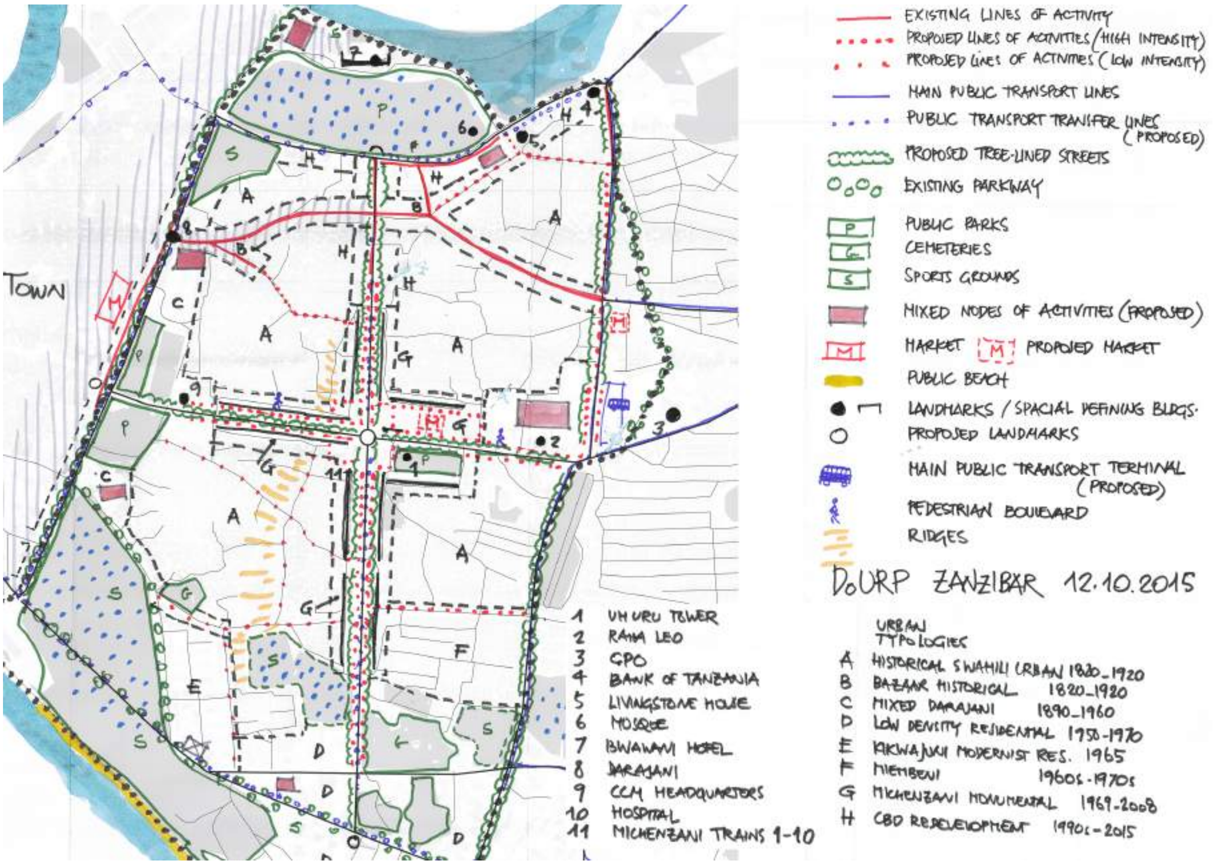

Figure 5: First sketches of the future land use of the Study Area. Edited from the original supplied by the DoURP

6.1.1 Typical Architecture and Typology

The typical traditional residential housing, so called Swahili houses, which the main part of the study area consists of developed from the indigenous Zanzibar dwellings made of wattle and daub constructions with thatched makuti roofs of palm leaves (Syversen, 2007). They developed together with the Swahili culture through influences from all over the world, for a complete history see Inger Lise Syversens PhD-thesis *Intentions and Reality in Architectural Heritage Management* from Chalmers University (2007). The houses nowadays often consist of coral stone walls, mangrove roof beams and metal-sheet roofing, see figure 6. The 'coral stone' refers to a 350 mm profile mix of coral rag with mud on timber structure. Modern elements of the houses include walls made of cement blocks, concrete elements and multi-storey versions. Houses often have barazas, stone benches, beside the front doors, which make up a semi-private sitting area in the shade of the house. The houses are arranged quite densely in a free pattern and many different architectural typologies such as modern, traditional and multi-storey are spread throughout the area, giving it its charming flair, see also figure 7.

Figure 6: Different traditional Swahili houses made of coral stone and cement blocks. Top-right picture by Inger-Lise Syversen.

Figure 7: The density and contrast of housing typologies in the study area.

Temperatures in the traditional Swahili dwellings can be quite hot. For a house in the study area these, compared to outdoor values, can be seen in figure 8, which shows continuously measured values for one week. It shoes how the outdoor temperature varies with a daily rhythm, reaching up to around 30 °C during the day and dropping down to around 24 °C at night. The temperature inside the house however, stays quite constantly at around 27 °C, varying only slightly. This particular house, belonging to Master Masudi, is located in the north-west of the study area (Mutonga, 2014), see also the blue star on the photo of the study area, figure 4. Its construction consists of a 350 mm thick coral block wall laid in cement, sand, mortar and plain plaster. It has a thin lime plaster finish on the exterior walls. The roof construction consists of a timber frame covered by corrugated iron sheets. Coral rag has been filled into the roof construction to prevent heat absorption into the interior.

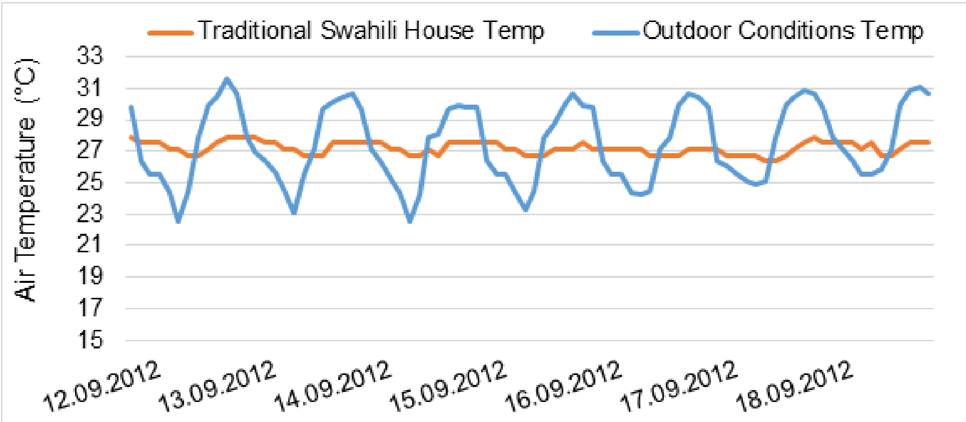

FIGURE 8: Actual measured temperatures in a traditional Swahili house in the study area compared to outdoor conditions. Graph is based on the measurements by Mutonga (2014)

6.2 Screening

The strategic action at the base of this case study is prompted by a need of structuring and gaining control over the unplanned residential areas outside of Stone Town. The aim is to raise living conditions and increase resilience, based on a thorough assessment of the area made by the consultancy firm Shapira & Hellerman Planners ROM Transportation Engineering Ltd., sponsored by the World Bank (Government of Zanzibar, 2014). The subject of this specific strategic action plan titled 'City Centre' is to develop a new land use plan that the current community can grow into, for the 238 ha large urban area directly outside of Stone town, Zanzibar. The plan is at a comprehensive level and includes the zoning of areas such as roads and low-density residential areas, and includes restrictions on building cover and building height. The strategic action is a voluntary improvement plan by the official authorities with the Strategic Environmental Assessment also being voluntary. The geographic area can be seen in figure 4 and the departments vision is to make a Smart, Green, Vibrant City. The strategic action is spatial and should have a temporal scale of at least 14 years, i.e. to the year 2030.

For this assessment the framework of a base-line led SEA with a topic-based approach is an appropriate choice, as one of the delimitations of this research is to only include Urban Climatology and Climate Change adaptation issues. The study is performed by the researcher as a consultant in direct collaboration with the decision-maker, the DoURP. Other involved actors include the Zanzibar Department of Environment (ZEMA), the architecture firm African Architecture Matters and the inhabitants of the study area.

6.3 Scoping

First the policy context of the strategic action is described including objectives and regulations. Also restrictions posed by other political documents are discussed. Then the environmental baseline is described including the current climate, LULC and the surface temperatures. A summary of the results of the brief questionnaire filled in by some of the inhabitants is also presented.

6.3.1 The Policy Context

Proposed objectives of the strategic action are to:

- Enable and support the upgrade and enhancement of the study area
- Ensure optimal utilisation of high value Real Estate
- Protect, nurture and enable the upgrading of commercial functions in the city
- Ensure adequate scale and appropriate standard of real estate to meet the needs and projected demand for the developing business sector and for government institutions
- Enable the study area to serve as the functional centre and gateway to Zanzibar and as a tourism attractor in its own right whilst protecting and utilising the city's unique culture, architecture and urban fabric
- Direct the spatial distribution of land-uses, infrastructure and redevelopment in the area whilst enabling specific segments and quarters to serve specialised functions and retain unique character
- Enable the systematic, staged upgrading of infrastructure throughout the city centre
- Prioritise pedestrians in the high density, high intensity segments of the city centre
- Enable high standard public transport services ensuring effective access to the study area
- Allow for synergies and propose solutions and recommend spatial location for the assorted land uses competing for space in the study area
- Enable upgrading of the residential stock for a population of at least 30,000 and a possible population of 50,000
- Recommend development priorities with the due consideration for city and local scale requirements and capacities
- All with due consideration for relevant environmental and safety constraints

Other proposed regulations in addition to the objectives regarding new, modern, high-density residential development that could affect the SEA are discussed below. These include that commercial fronts are allowed only on certain roads that have appropriate access; provision of adequate parking and special requirements as defined in detailed planning. This indirectly encourages the population to go shopping by car, which could increase the anthropogenic heat flux. The culture of the people that includes shopping on foot at neighbourhood stores and local markets is also not encouraged by this regulation. Another regulation states that all structures in high-density zones must be open to the street. This could increase the order in residential areas and prohibit the unplanned development of housing, which could have positive effects on the density of residential areas and increase open spaces. Finally requirements of floor area ratio (FAR) are made that can have large effects on the density as well. This is the ratio of a buildings total gross floor area to the size of the plot of land on which it is built. This affects the density of urban areas the proposed values for which are maximum coverage of 50% plot area with FAR 1.2 - 1.79, maximum coverage of 45% plotarea with FAR 1.8 - 2.39 and maximum coverage of 40% plot area with FAR 2.4 - 3.0. These will be modelled and discussed in different development alternatives.

Another document that has an influence on the strategic action and the SEA is the strategic plan 2013-2015 from the DoURP which states that aims of the department include to:

- Enhance the spatial planning system to strengthen the equity and quality in social, cultural and economic development
- Co-ordinate land use at all levels and all sectors for a quality environment and sustainable uses of cultural and national resources
- Enforce and strengthen implementation and monitoring of plans, guidelines and regulations
- Facilitate stakeholders awareness, participation, empowerment and coordination to ensure good governance in urban management
- Build a conducive environment responsive to social, cultural and economic development
- Develop vibrant, good quality and sustainable city and towns to strengthen competitive urban economy
- Main-streaming gender equity and cross-cutting national agendas in the planning system

Objectives and strategies found in this strategic plan that are directly relevant to the new strategic action and the SEA include:

- Objective 2.1 Increase public participation in planning and implementation of land uses by:
  - Strategy 1: Increase roles and ownership of public planning
  - Strategy 2: Effective use of mass media for information dissemination during planning and implementation
  - Strategy 3: Improve coordination with other sectors on land issues

– Strategy 4: Promote public private partnerships in planing and development

- Objective 3.2 Support environmental and climate change adaptation by:
  – Strategy 1: Support environmental issue and protection of sensitive areas incorporated in planning process
- Objective 3.5 Support initiatives of accessibility to adequate and affordable housing by 2015 through:
  – Strategy 1: Prioritise initiatives of housing accessibility agenda through planning

6.3.2 The Environmental Baseline

Zanzibar, just south of the equator, has a tropical oceanic climate with small seasonal variation in day length, temperatures and humidity but with large fluctuations in rainfall (Gillespie and Clague, 2009). The seasonal variation of rain fall is due to the inter-tropical convergence zone (ITCZ), which is the area encircling the earth around the equator where the north-east and south-east trade winds come together. The main rain season lasts from March to May with heavy daily downpours and maximum average temperatures slightly above 30 °C (Tanzanian Meteorological Agency, 2012). The monthly rainfall during this rain season varies quite a lot, for example in 2011 it rained 50 mm in March, 450 mm in April and 250 mm in May, see also figure 10, whereas in 2012 it rained 150 mm in March, 170 mm in April and 120 mm in May. This is followed by the long dry season between June and October, which is also the main tourist season. In these months rain is quite uncommon, in general under 50 mm per month, and it is also the coldest time of year with temperatures ranging from 22-30 °C. The short rain period from the end of October to the beginning of December consists of lighter and less reliable rains and is followed by the two hottest months January and February, during which average temperatures do not go below 24 °C. The total rainfall lies between 800 and 1600 mm per year and the mean temperature is 27 °C. It rains to a certain degree all year round even throughout the dry seasons, the driest months being February and July.

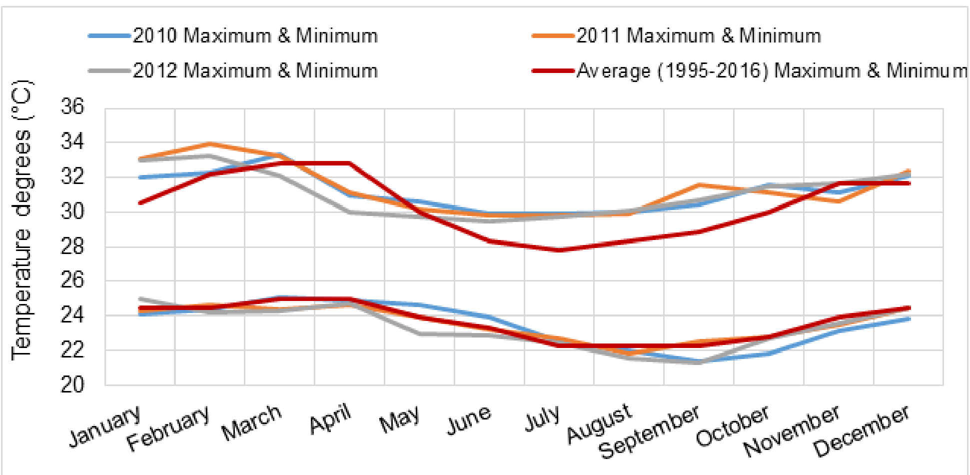

FIGURE 9: Monthly mean maximum and minimum temperatures as measured at the meteorological station at the Zanzibar Airport for the years 2010-2012 and the average for the years 1995 to 2016 (Tanzanian Meteorological Agency).

Because of the relatively high humidity, vegetation in general survives the dry months. The average humidity is very high and ranges between 75 to 88 % see figure 12. The average daily and

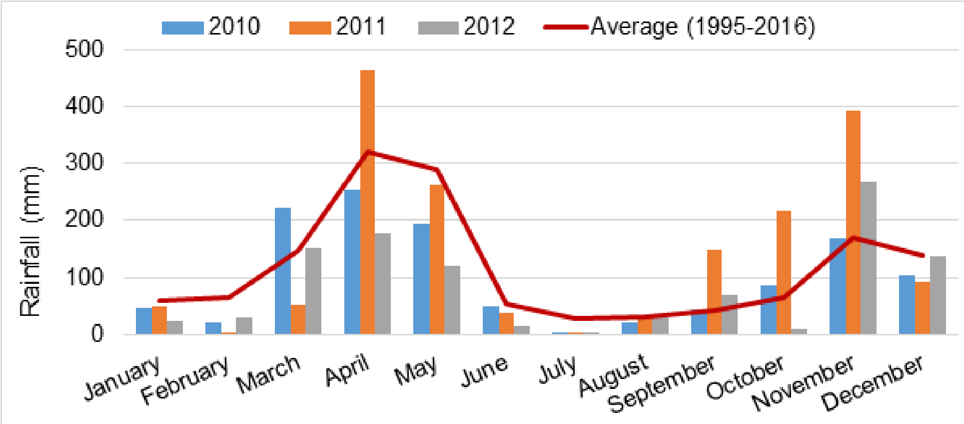

FIGURE 10: The monthly rainfall as observed at Zanzibar Airport for the years 2010 to 2012 and the average over the years 1995 to 2016 (Tanzanian Meteorological Agency).

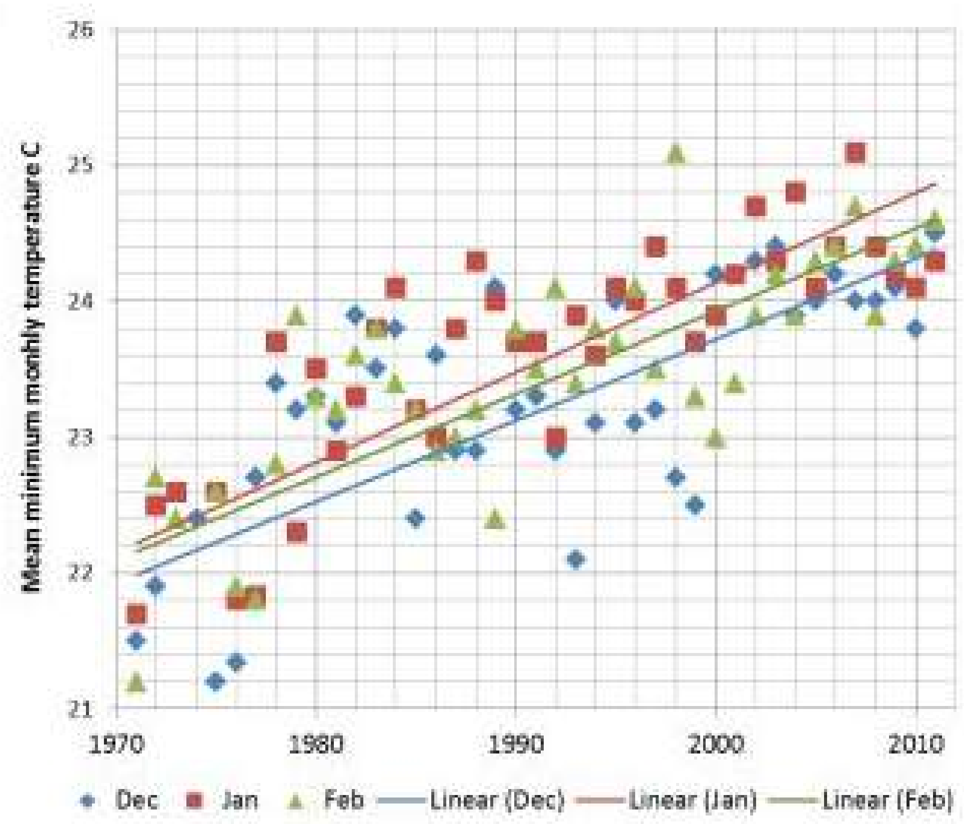

FIGURE 11: The minimum temperatures on Zanzibar Island are experiencing a trend of slow increase. As the temperatures are measured at the meteorological station at the Zanzibar airport this could have several reasons, such as global warming or urbanisation (The First Vice President's Office, 2012).

monthly maximum and minimum temperatures range from a minimum of 21 °C to a maximum of 34 °C and can be seen in figure 9. The temperature trends in recent years have seen a slow increase of average minimum temperatures, which implies that it does not cool down as much during the nights. Note however that care needs to be taken when interpreting this trend as it shows data from a relatively short period that could have many explanations (The First Vice President's Office, 2012).

The south-east and north-east trade winds blow across Zanzibar, and the average monthly wind speed and direction is shown in figure 13 as measured at the Zanzibar Airport meteorological station. Note that the values come directly from the Meteorological Agency of Tanzania and no information was given as to how the average values were calculated. The months January - December are represented by the numbers 1-12, the wind speed is seen on the left vertical axis and the wind direction is represented by the blue arrows, with North being towards the top of

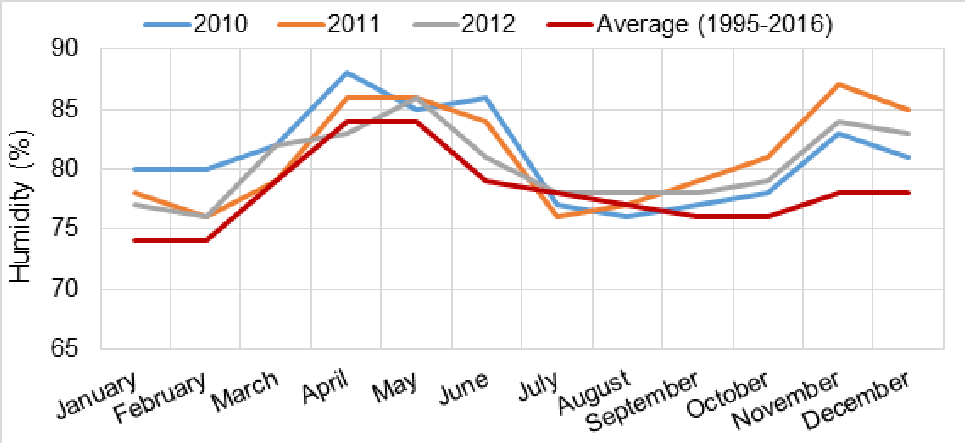

Figure 12: The mean monthly relative humidity as observed at Zanzibar Airport for the years 2010 to 2012 and the average 1995 or 2016 (Tanzanian Meteorological Agency).

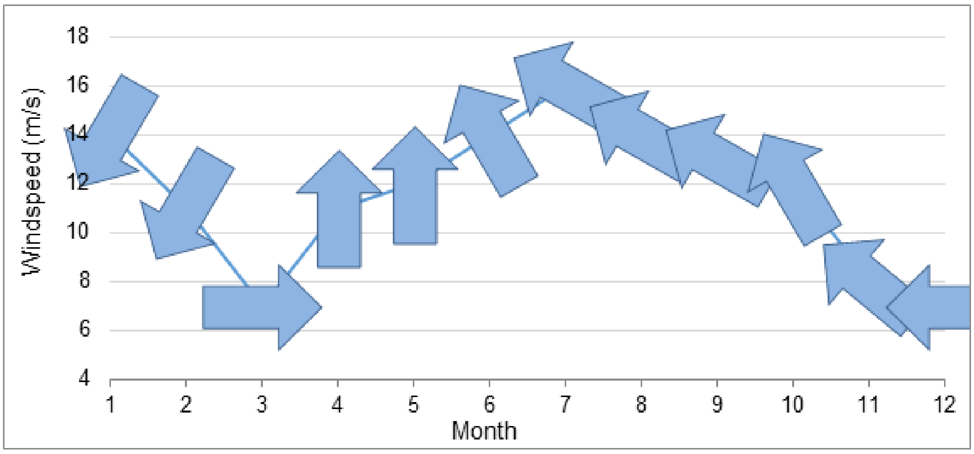

Figure 13: The average monthly wind speed and wind direction, with North being towards the top of the page. Measured and averaged at the meteorological station at the Zanzibar Airport (Tanzanian Meteorological Agency).

the page. As can be seen the winds are strongest in the months of January, June, July and weakest in the months of March, November and December. The wind directions vary throughout the year, note however how these are the average wind directions for a month and the variations throughout the months or individual days are not shown.

6.3.2.1 Land Use and Land Cover Classification

The LULC for the study area is classified according to the UMT system, see figure 14. The main part of the study area is extremely densely populated, with the residential buildings constructed according to traditional Swahili architecture. The smaller roads are often framed by more modern buildings termed 'Indian Shop-front' by Syversen (2007), however included in the UMT category 'Modern low-rise' in this report. These are three storey concrete structures that contain commercial uses on the street level and residential uses on the first and second floor. 'Modern mid-rise' buildings are established along the main roads and in the north of the study area. These include the famous Michenzani flats which are massive apartment blocks built by Karume along the main roads in the late 1960's with the help of East Germany. Parks, sports grounds and other open spaces are mainly located in the south and the east of the study area, along the beach and between Ng'ambo and Stone Town along the old Creek Road. The small area of mangroves in the north of the area usually does not show up on land use plans or maps of the area, as the border in the north is usually defined as the end of land and start of ocean. However, as it is deemed that it is an important area to keep and protect it was chosen to be included in the study area so it is not simply forgotten, especially as it is currently largely framed by highly trafficked roads leading inland.

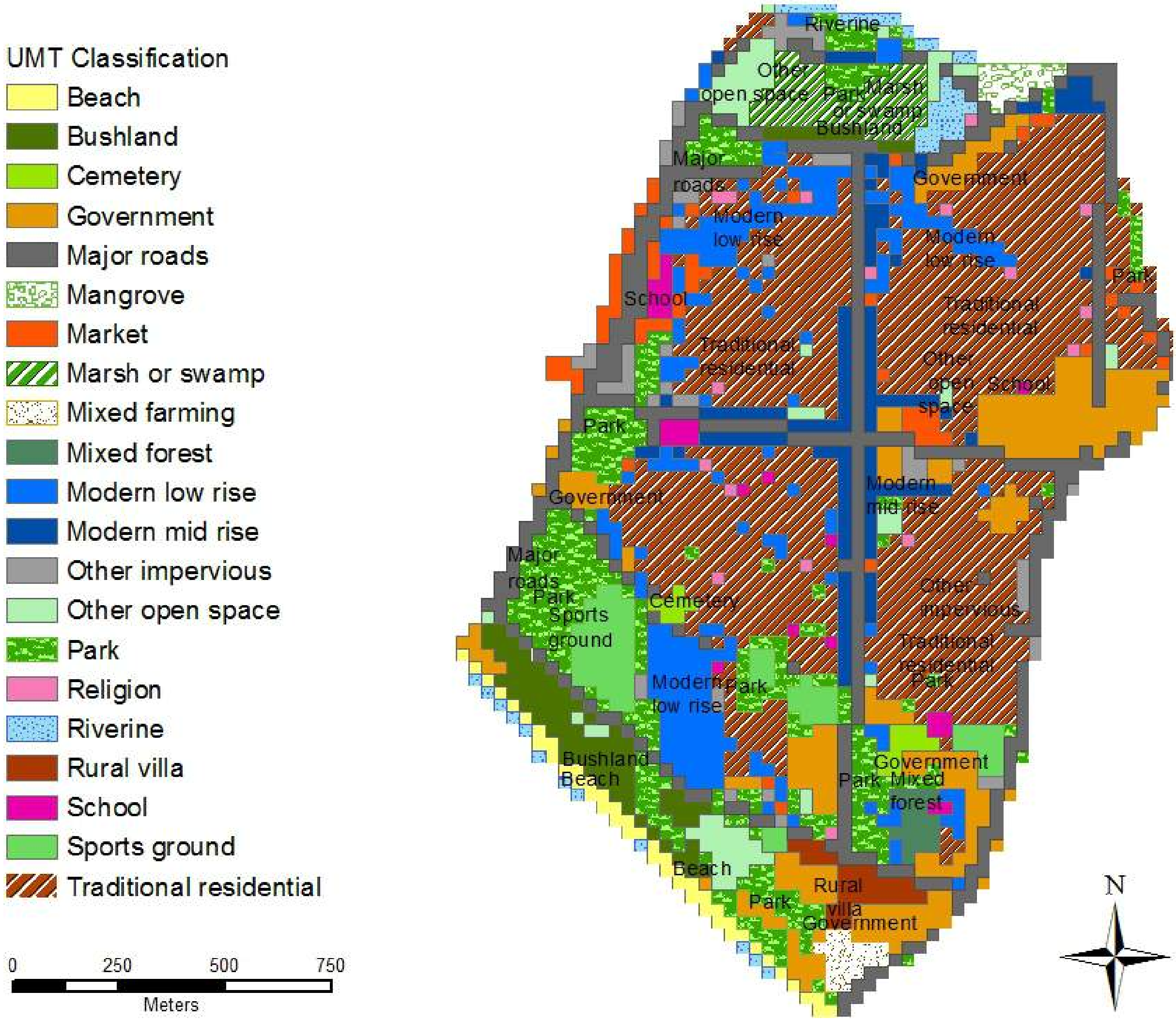

FIGURE 14: The land use and land cover of the study area classified according to the UMT system, adapted from Gill et al. (2008)

Each of these UMT categories was analysed according to their average surface cover composition and the results were used for the modelling. It was estimated for example, that in the dense residential areas up to 70% of the surface is covered by buildings, 10% vegetation, 10% bare soil and 10% by other impervious surfaces, such as small roads or other paved areas. The category 'Government' on the other hand only has a 'built-up area' cover of approximately 12%, an 'other impervious' cover of 10%, 28% 'bare soil or sand' and a total of 55% is covered by vegetation. This implies a large difference in both amount of free, open space and the degree of vegetation in the area. The UMT category 'School' which gathers all educational buildings is quite similar to the category 'Government', with 10% building cover and 60% vegetation. The largest degree of vegetation is reached by the 'Mixed forest' area in the south-west of the study area, and the lowest by the category 'Markets'. These include all form of market arrangements in permanent or non-permanent buildings, such as containers. The market areas have an extremely high cover of impervious surfaces including 48% 'built-up' areas, 5% 'roads' and 20% 'other impervious' which sums up to a total impervious cover of 73%. The UMT category 'Major roads', not to be confused with the surface cover 'roads', has a surface composition contained of 5% 'built-up' area, 50% 'road' surface cover, 5% 'other impervious' cover, 23% is covered by vegetation or water and 17% of 'bare soil or sand', see also the middle picture in the bottom row in figure 2. The surface cover for the other areas can be seen in figure 15.

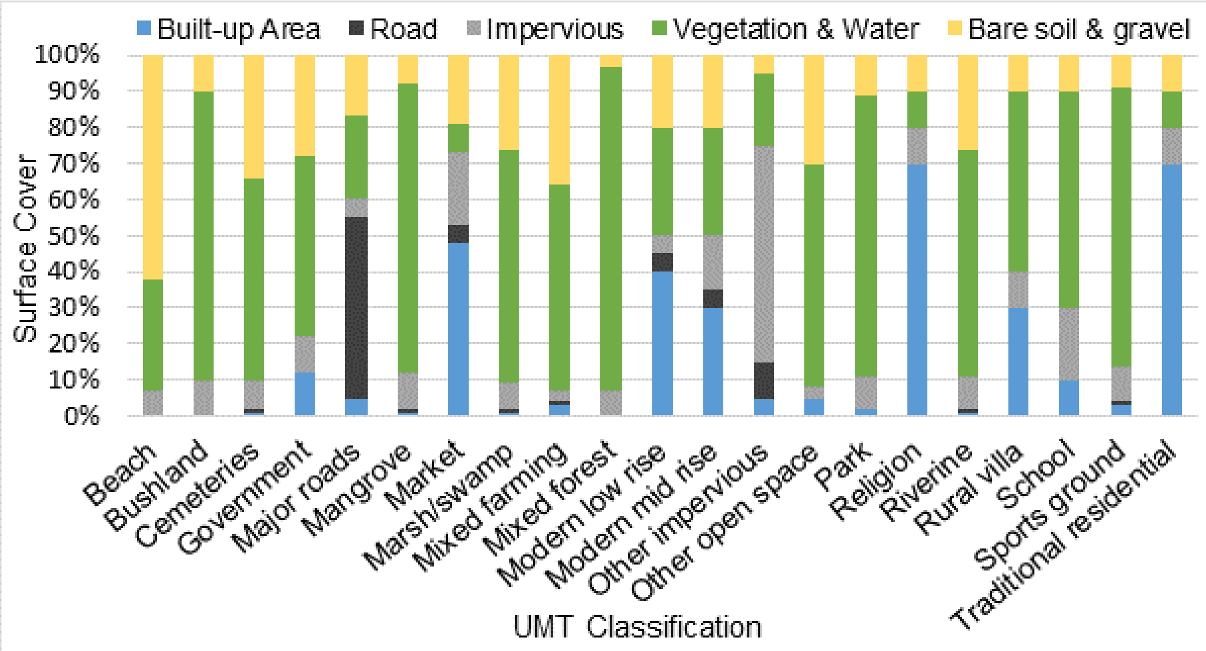

Figure 15: Approximated current surface cover composition for the study area, which shows the percentages of ground that covered by 'built-up area', 'road', 'impervious', 'vegetation & water', and 'bare soil % gravel'.

This assessment is very important for the modelling of LST as it establishes the fluxes in the SEB. Most important for this is the evaporative fraction i.e. the surface cover percentage that is labelled 'Vegetation & Water'. The spatial distribution of vegetation and other evaporative areas for the different UMT categories can be seen in figure 16. It corresponds directly to the green coloured area in figure 15, and shows that the UMT categories with the highest percentage of green or blue cover are the recreational areas, in no particular order they include parks, cemeteries, sports grounds, marshes and swamps, bushland, riverine and forest. More interesting is that, of the built-up areas, the ones with the higher degree of evaporative surfaces are governmental areas, educational facilities, modern mid-rise areas and rural villas. The least amount of evaporative surface cover can be found in the dense, traditional residential areas, religious facilities and other impervious areas, which include parking lots etc. In the middle we find the UMT categories major roads and modern low-rise.

6.3.2.2 Modelled Baseline Mean Radiant Temperatures

Using this data, along with other input (see figure 3), for a first run of the MRT model the current surface temperature distribution is modelled for the period 1981-2000 as seen in figure 17. The MRT for the different UMT categories varies between 27.5 - 47.6 °C. The hottest MRT values are reached in the traditional residential areas, and the coolest in parks. The major roads also have quite high MRT, along with markets, impervious areas, mosques, modern low-rise areas and the

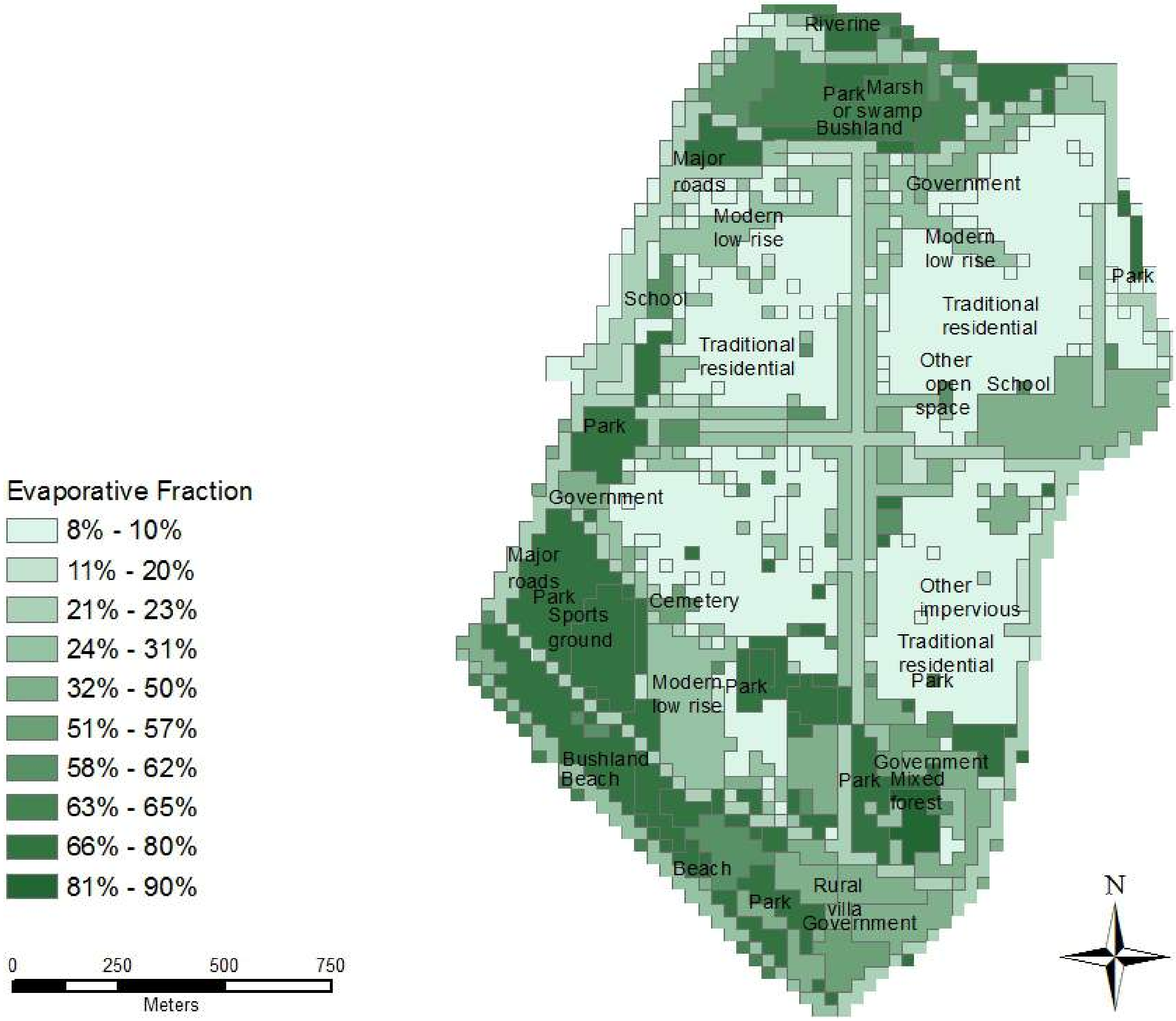

Figure 16: Approximated evaporative fraction for the different UMT classes throughout the study area.

beach. Cooler MRT is seen in areas such as sports grounds, bushland, schools, governmental plots and mangroves.

When plotting the MRT values against the evaporative cover fraction, the percentage of land covered by vegetation or water, it can clearly be seen how an increased evaporative fraction implies lower temperatures, see figure 18. For most UMT categories, the higher the evaporative fraction, the lower the surface temperatures. This is not true for the category 'modern mid-rise' that achieves a quite low MRT of approximately 32.8 °C even though the evaporative cover only lies around 30 %, compared to modern low-rise that has the same cover of evaporative surfaces but has a MRT of 36.5 °C. Also the category 'Religion' which mainly includes small mosques and Indian temples is slightly off trend with an MRT approximately 4.5 °C lower than the traditional residential areas with the same surface cover composition.

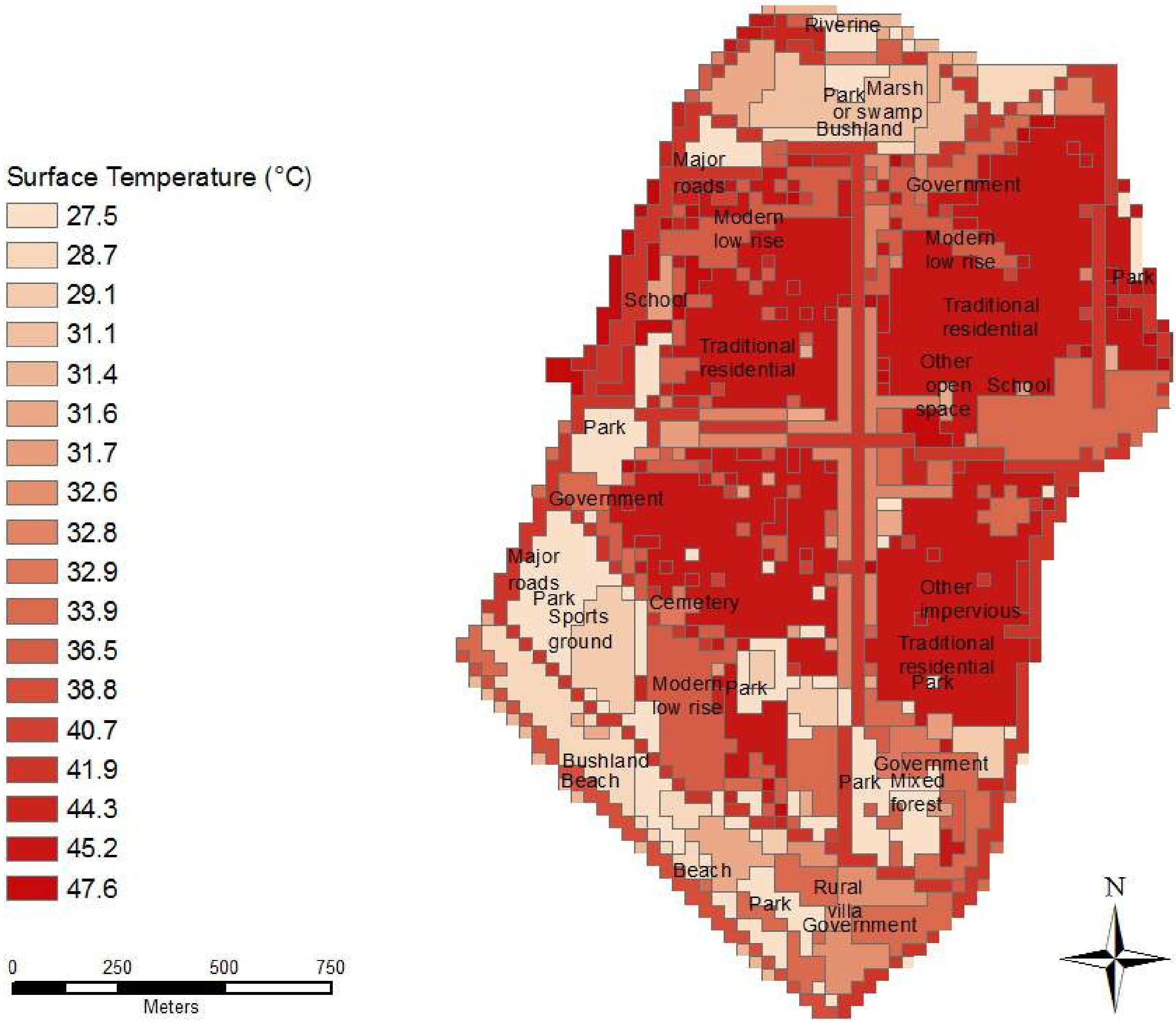

Figure 17: Base line temperature in the study area modelled with STAR tool developed by Gill et al. (2008)

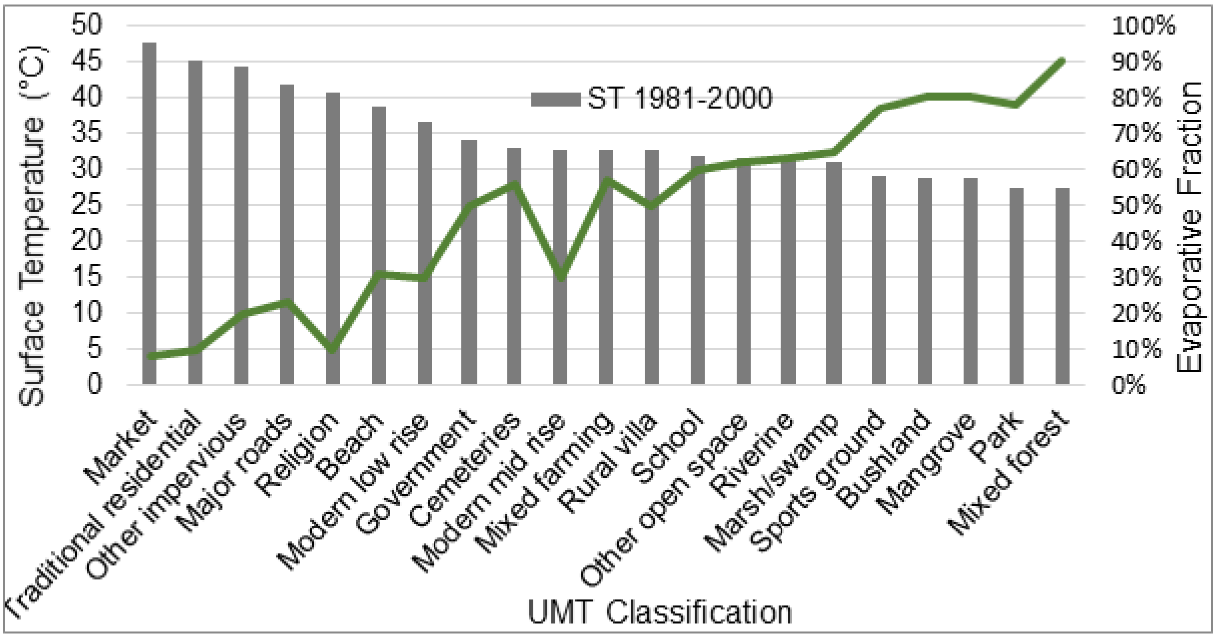

Figure 18: The graph shows how, for the baseline scenario, the surface temperature quite clearly relates to the evaporative fraction of the surface cover.

6.4 Analysis of Alternatives

In this section the outcome of the modelling of the different alternatives is presented. First the land use changes presented by the DoURP are described. They are shown spatially through a new UMT classification, and the future surface temperatures are modelled. After this different alternatives of surface cover composition are modelled. These all follow the same spatial distribution of UMT categories, and the different modelled alternatives represent different legislation options of surface cover. The worst case scenario is modelled by a reduction of the evaporative surface cover with 50%. As the main issues perceived in the baseline scenario are in the dense traditional residential areas the following alternatives concentrate on these. Different options of building density are modelled and the freed-up space is either spread out evenly amongst the other categories, or turned solely into evaporative surface cover.

6.4.1 Changes in LULC by the DoURP

The results from the manual UMT classification for the redevelopment scenario of the DoURP can be seen in figure 19. It is based on the sketch of the new land use plan seen earlier in figure 5 and the grid cells in ArcGIS were altered accordingly. The main differences are the spreading of modern mid-rise development close to the main roads, and the extension of the formal roads into the residential areas. More formal parks and sports grounds are created from 'other open space', and in the south of the study area low-density residential areas have been established. These have been defined to spread north into the area and replace some of the dense residential areas. The swamp basin in the North is kept as it serves important water run-off functions and some sports grounds with the same flooding function exist in the south. This keeping of the basin in practise has been largely discussed and might be outside the control of the DoURP. The UMT category of 'Schools' shows a decrease, as the DoURP plans to move these away from their current locations. They are often in inconvenient locations such as in the middle of the busy market district in the west of the area or close to the major roads. It can be seen for example in figure 19 that the market district has been enlarged in the west replacing the school. No new areas for the schools have been planned in detail however, and so these do not show up in the new land use plan yet. The small area of 'Mixed farming' has been re-zoned to a sports ground but the forest area is kept.

A new land use class is introduced to the UMT categories as a bus-terminal is planned in the east of the area. This is aimed to serve the local and regional bus traffic for the whole city. It also has to be noted that this UMT classification shows the 'final result' of the land use plan if it is possible to be followed through, and it does not show stages of the gradual change that will take place.

If the DoURP strategic action changes the land use of the area, but does not start any regulations regarding the surface cover composition, and if it can be estimated that it therefore does not change within the UMT categories, the expected temperature change for the period 2020-2050 can be seen in figure 20. Surface temperatures are expected to rise between 0.4 and 0.7 °C within the different UMT categories compared to the baseline, and the spatial distribution of higher and lower temperatures in the study area is altered through the changed land use.

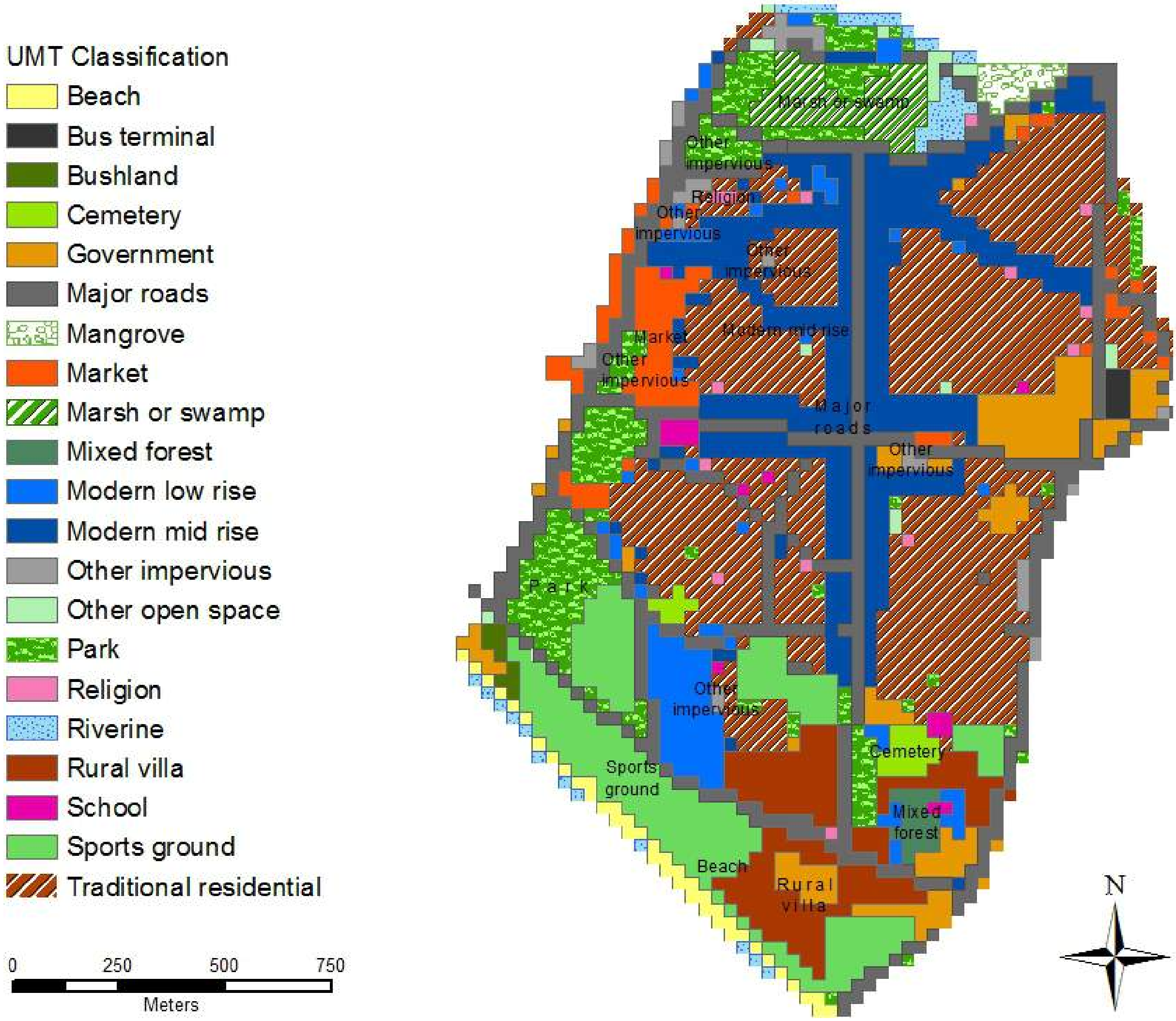

Figure 19: This figure shows the different land uses of the study area after the redevelopment according to the plans of the DoURP. The main differences to the current land use are the development of modern mid-rise buildings, and open space being turned into parks. This shows the land use after the redevelopment and does not account for the stages of gradual change. Adapted from the Urban Morphology Type developed by Gill et al. (2008).

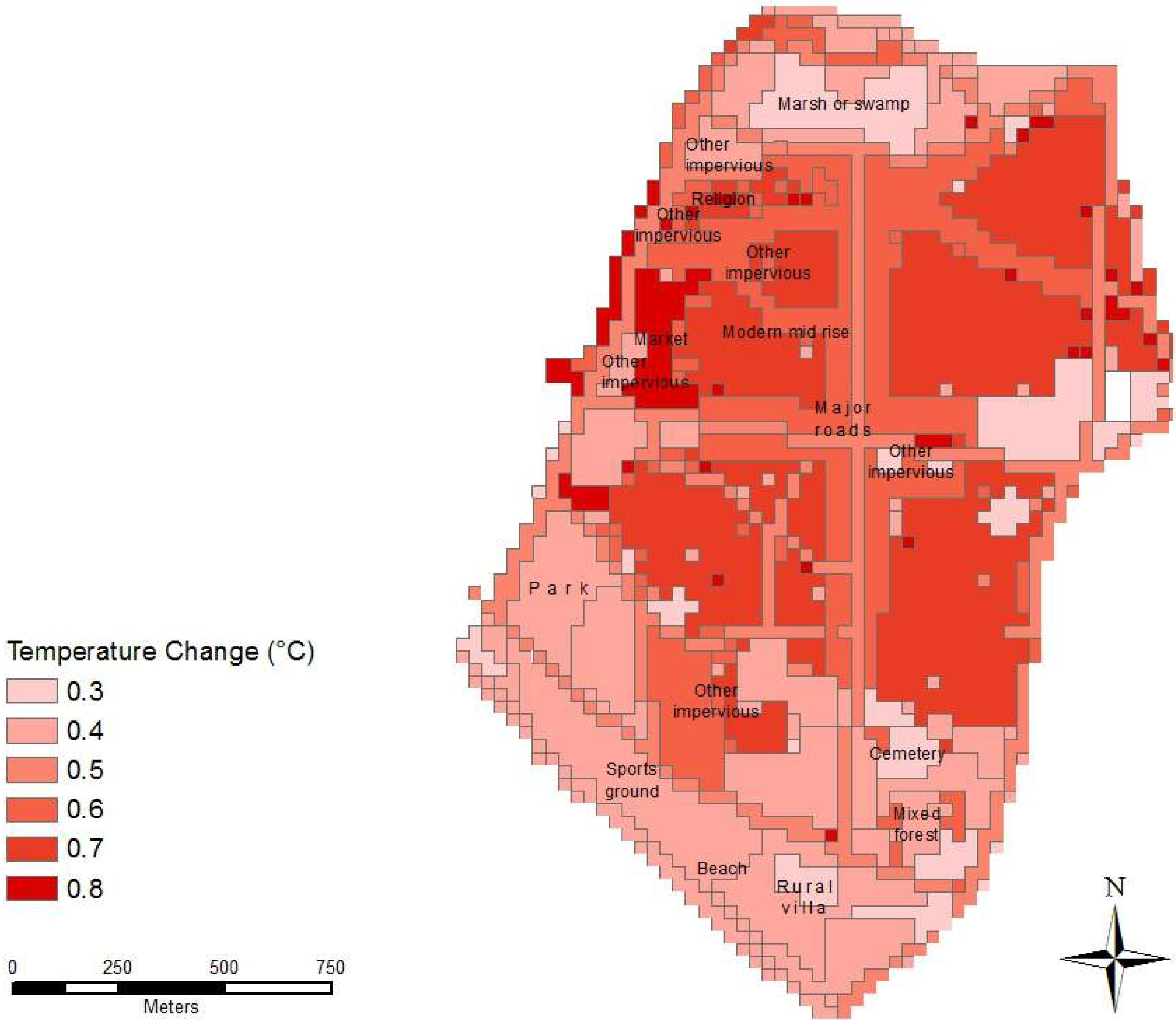

Figure 20: Future temperature of the altered study area with no changes in surface composition for the planned land use by the DoURP modelled with STAR tool developed by Gill et al. (2008). This change in temperature is based on the IPCC climate change scenario SRES A1FI and shows the 50% probability central estimate. This is modelled through a largely simplified SEB model and the main purpose is not to present a reliable estimation of global warming. The purpose is as a comparison to the other modelled alternatives that include changes in surface cover composition.

6.4.2 Best Case Scenario

An improvement in the surface composition is modelled as a best-case scenario. This involves an increase of the evaporative surface fraction with 20%, which is taken from the surface cover category 'bare soil or sand'. This increase in vegetation cover is however only applied to UMT categories with an evaporative cover of less than 50%. This means that the surface cover of the land uses park, sports ground, riverine, mangrove, government, rural villa and school was not altered, while the land uses of major road, residential, market, bus terminal and other impervious were altered. The results show a decrease in temperatures between 0.1-1.7 °C, see figure 21. The white areas in the figure represent the areas that were not altered, and thus no change was modelled.

Figure 21: This figure shows the decrease of modelled surface temperatures for the different UMT categories when modelling the best case scenario, an increase of the evaporative fraction by 20% in UMTs with a evaporative fraction cover of less than half. It shows a decrease in future surface temperatures of up to 1.7 °C compared to the global warming scenario in figure 20.

The largest difference of 1.7 °C can be seen in the UMT category 'Major roads'. Up to 1.4 °C change was modelled for the categories 'Modern low-rise', 'Religion', and 'Other impervious', while changes of 1.0 °C were modelled for 'Modern mid-rise'. The traditional residential areas show a decrease in surface temperature of 0.7 - 0.9 °C.

6.4.3 Worst Case Scenario

To estimate how important the vegetated areas are, all evaporative surfaces in all UMT categories were reduced by 50%. This is a drastic reduction but represents a worst-case scenario where the importance of green areas in cities is not recognised, or if vegetation dries up due to less rain between rain seasons. The corresponding land surface composition can be seen in figure 22, where the evaporative fraction for each land use has been halved and the freed-up area split evenly into 'bare soil or sand' and 'other impervious'.

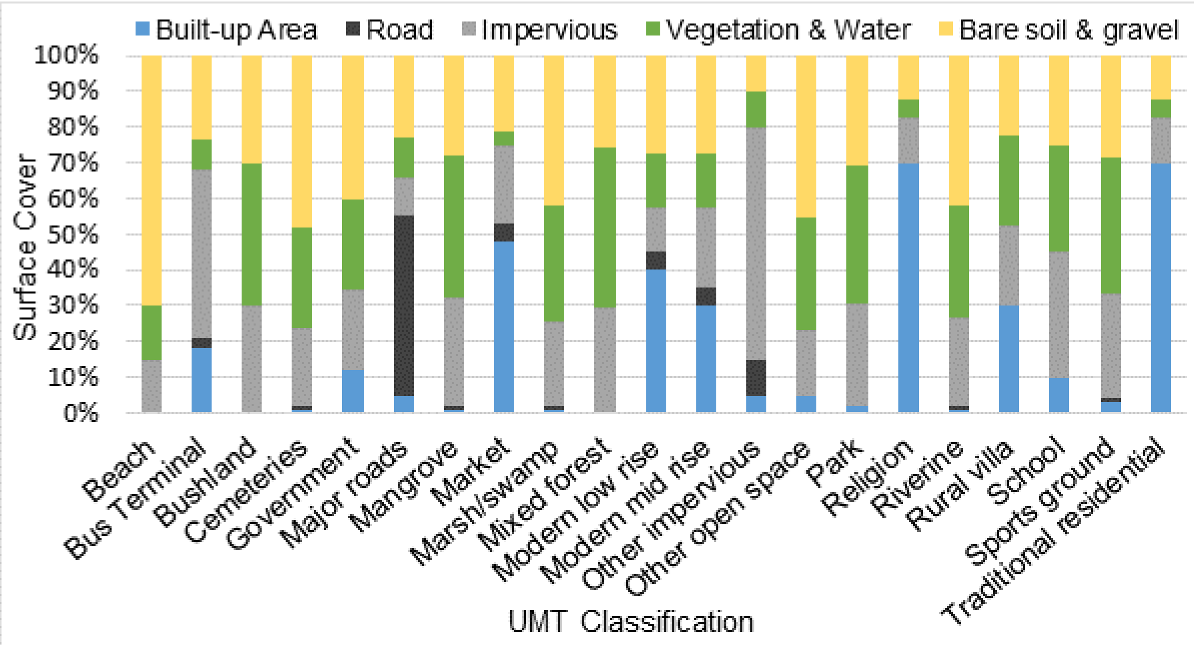

FIGURE 22: The changed LSC composition with a 50% reduction of evaporative areas compared to the baseline scenario. The freed-up surface cover is distributed equally between the surface covers 'bare soil or sand' and 'other impervious'.

This reduction could result in the quite drastic increase of surface temperatures seen in figure 23, approximately between 4 and 10 °C. The largest changes can be seen mostly in UMT categories with a high percentage of evaporative surface cover such as parks, sports grounds and cemeteries. An exception is the category 'Bus terminal' which shows the highest modelled surface temperature changes of 10.8 °C. It must however be noted that the bus terminal will be constructed on land that is now governmental which implies major changes to surface cover composition. The category 'beach' ends up with a surface cover that consists of 70 % 'bare soil or sand' and also shows a very high surface temperature increase of around 9 °C. Even in areas that only have 5% of vegetative surface cover before the reduction, such as the traditional areas, a surface temperature change of 4.5 °C was modelled. The UMT with the lowest change in surface temperature of 3.8 °C is 'Religion'. As the UMT category 'Religion' has the same surface composition as "Traditional residential' this must be influenced by the high building mass of mosques.

The relation between the surface temperature and the evaporative fraction that was seen in the baseline scenario can still be shown even with the high reduction, see figure 24. The temperature differences between UMT categories are not as large as in the baseline scenario with a variation of around 6 °C, and also the evaporative fraction is more even, varying from 2.5% to 45%. This makes the correlation less pronounced, but it is still clearly present. Again some categories do not follow this trend, the categories 'Modern low-rise' and 'Modern mid-rise', and the category 'Religion'.

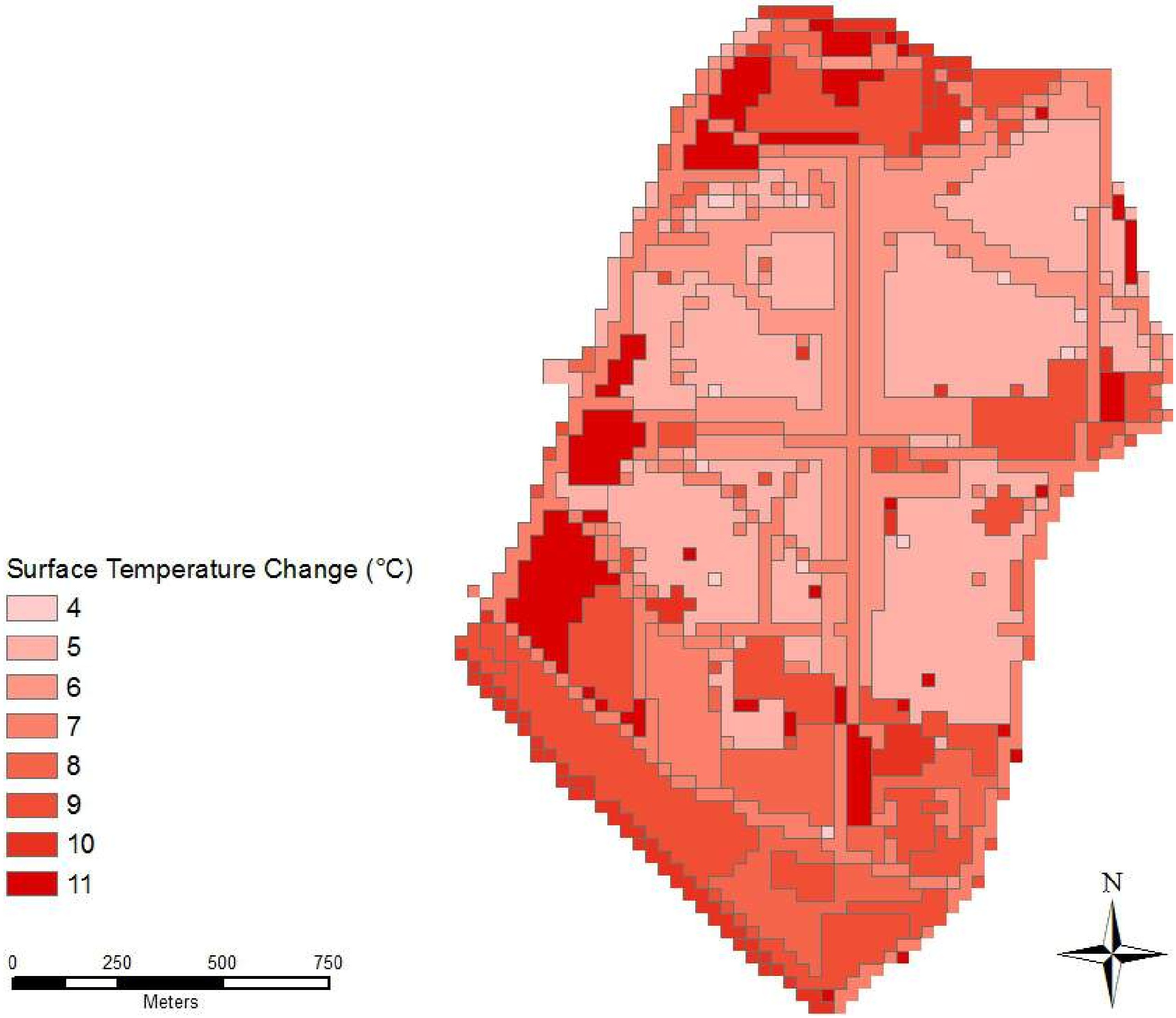

FIGURE 23: This figure shows the increase of modelled surface temperatures for the different UMT categories when modelling the worst case scenario, a decrease of the evaporative fraction in each UMT by 50%

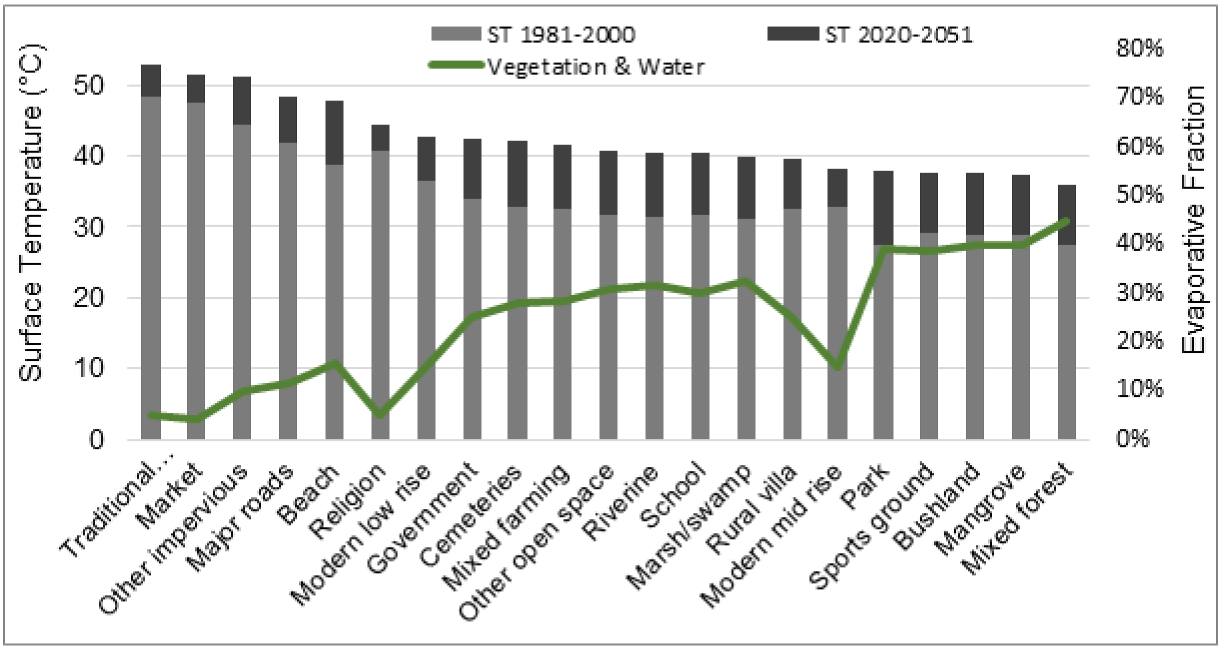

FIGURE 24: The correlation between surface temperature and the evaporative fraction is shown in this figure. Both the baseline and the future modelled surface temperatures can be seen for the different UMT categories. UMTs that differ from the trend are 'Modern mid- and low-rise' and 'Religion'.

6.4.4 Traditional Residential Areas

The traditional residential areas showed a very high surface temperature already in the baseline scenario, the estimated 45 °C can be compared to the temperatures of parking lots or mayor roads, 44 and 42 °C respectively. This may be due to the high density that these areas show compared to other residential areas. As the DoURP seeks to keep and encourage this traditional housing, a few alterations have been modelled which could improve the well-being of residents. Scenarios of reduced density and increased evaporative surfaces have been modelled and can be seen in the following figures below. In the first scenario the percentage of surface area covered with buildings is gradually decreased from 70 to 20 % and the resulting free ground is divided evenly between 'impervious surfaces', 'bare soil or sand' and 'evaporative areas'. In the second scenario the building cover is decreased in the same way, but the entire freed-up surface is turned into 'evaporative areas'.

It can be seen in figure 25 that the surface temperature can be decreased between 1 - 6 °C for the scenario where freed-up surface areas are divided equally among the three different surface covers 'impervious surfaces', 'bare soil or sand' and 'evaporative areas'. However, if the freed-up surfaces areas are converted into green space exclusively, a decrease in surface temperature of up to 15 °C is possible, if the density is decreased to 20%, see also figure 26. This implies, that even if the density is not changed, turning bare soil, sand or impervious surfaces into grass, bushes and occasional trees, the surface temperature in the area could be reduced by around 3 °C, see again figure 26.

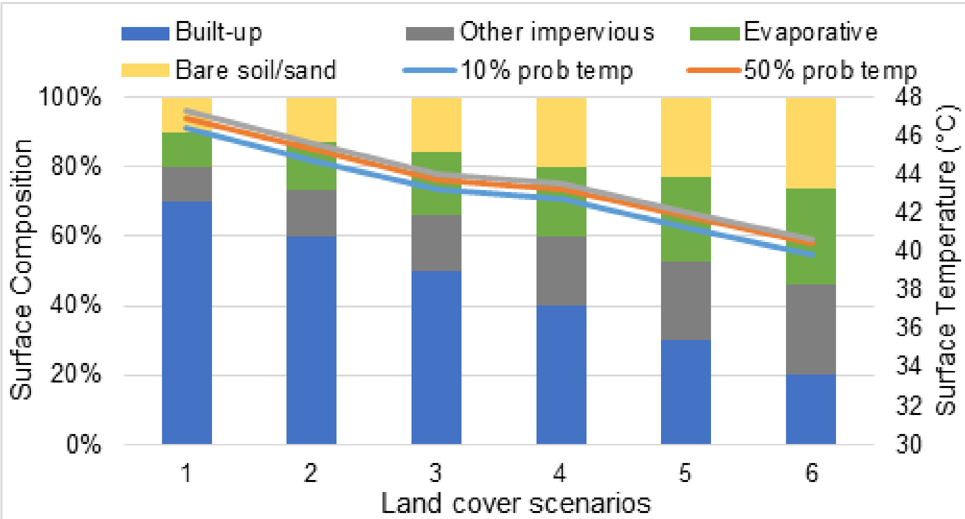

Figure 25: Temperature difference between density scenarios for the traditional residential areas, dividing the extra surface area evenly between other covers.

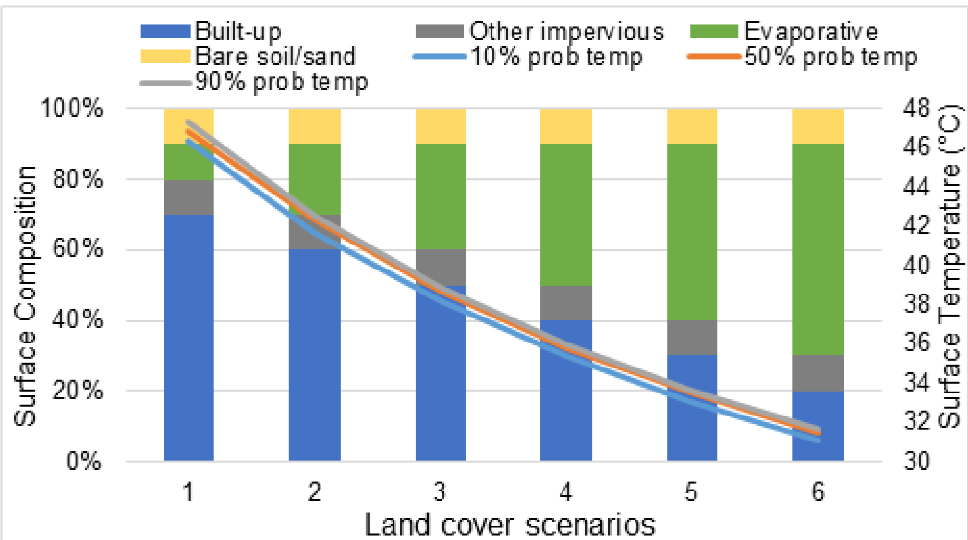

Figure 26: Temperature difference between density scenarios for the traditional residential areas, turning the extra surface area into evaporating surfaces.

7 Discussion

The results are discussed; first the methodology used, then the assessment of the climate model followed by the the case study, the use of SEA as methodology and finally the delimitations.

7.1 Discussion of the Methodology

Regarding the choice of urban climatology model, the methodology used can not ensure that all possible options were considered. The selection studied is rather limited, however the selection on offer was also quite limited in itself. Of all models studied not many were situation appropriate, some were too broad, some too detailed and others too complicated. In the end there was only the one model left as a plausible choice, and this one was used. The research could have benefited from more depth and validity by applying all available methodologies and running a comparative study however a reductive approach was necessary in order to complete this study within the given timeframe.

Even though climate change projection models can provide some important predictions or worst-case scenarios regarding the future climate, this study argues that they are not sufficient in creating resilient cities. Urban climatology has been studied for around 200 years and has become a basic resource broad enough to at least provide guidance regarding future city planning. This should be included when considering climate change adaptation as it could potentially provide great benefits.

It is important to look ahead and see the threat of climate change before it has reached us. In a hot climate like Zanzibar's, there is not a lot of clearance before matters become extremely dangerous and life-threatening. Urban temperatures can affect other issues for the better or for the worse. For instance rising temperatures may result in increased bacterial growth in pipelines or still-standing water, which potentially affects human health. As well as this, access to water and rapid response healthcare, is made more challenging by higher temperatures. Therefore, it is found, studying the issue of urban temperatures and global warming is a valid contribution to an improved plan for future urban development from an urgency point of view.

7.2 Assessment of Available Climate Models

The choice of models compared was based on a literature search on the Internet and on urban climate models used in earlier case studies or mentioned in reports. It could be possible that available and plausible models were not regarded in this study, as they were not discovered during the search. The way the models were tested is also subjective as it was based on one persons view and of course depends on personal knowledge and perception. No opinions from urban planners or urban climatologists were included in the assessment.

It is also debatable whether a climate model dependant on an Internet connection to function is an optimal choice, especially in developing countries. In the context of the DoURP however, where the case study was performed, the Internet connection is quite reliable, however, downloads are prohibited. In this case a model which does not require any download or installation is to be preferred. It is not the optimal case, but a plausible solution.

It also has to be said that using the quite simple model that was chosen brings with it a lot of benefits such as simplicity of use and thereby larger chances of actually being included in a planning process. However it also inevitably brings with it some drawbacks such as not including important aspects of climate change adaptation like surface water run-off and the creation of wind tunnels. There is a separate version of the STAR tool model available for surface water run+off that has not been included in this study as it focused on temperatures. Further, the important aspect of the choice of building material is actually included in the input data for the model but this study has not discussed that in detail. However the model could be used to analyse the impact of different local building materials.

The comprehensive scale of the model is fitting to the context and makes the adaptation of the land use plan to surface temperatures simple. However, more detailed studies might be necessary for individual projects.

7.3 Discussion of the Case Study

To classify the LULC a manual UMT classification approach was used. This could be seen as some-what subjective, but as it is performed by one person it is at least consistently subjective. According to Sobrino et al. (2000), for creating surface temperature maps at a neighbourhood scale, a scale of approximately 100 meters has often been appropriate. However, due to the rather small area studied, and the detail of the urban planning project in the case study, 30 meters was deemed a fitting resolution. This allows more control over specific neighbourhoods and is still classifiable through satellite images, if some knowledge of the area is accessible.

The STAR tool model used for the assessment of surface temperatures is designed for the context of Manchester, England. It states clearly in the instructions, that if used for a different context, the input values need to be correspondingly adjusted. Adjusted input values for this study were mainly based on Cavan et al. (2014) who used the model for a case study of Dar es Salaam. These could to a larger extent have been compared to other sources and better verified.

Other input, such as the calculations of road mass and building mass were also based on Cavan et al. (2014), but further adapted to the context of Zanzibar, through the detailed drawings of Zanzibar Swahili houses presented in Mutonga (2014). The averages of these throughout different UMT classes varied depending on storeys etc. However, these were not altered during the modelling for a sensitivity analyses, which could have been done to identify how important they are for the output temperatures. It can be seen however, that modelled surface temperatures differed for the two UMT classes 'Traditional residential' and 'Religion', and the only input differing for those is the building mass, that is higher for the category 'Religion', see also appendix A. This implies that building mass affects output surface temperatures.

The trend of rising minimum temperatures could cause increased heat stress and have an impact on human health. Usually the coldest times are during the night, and if the temperature during nights increases the body cannot regenerate from the heat stress experienced during the day. To prevent this the climatic properties of building materials should be considered. Both the absorption of heat which depends on albedo and mostly regards short-wave radiation, and the release of stored heat mostly regarding long-wave radiation, need to be considered.

As the synergy between climate change adaptation and mitigation is of great importance (Larsen et al., 2012) it is recommended that the DoURP collaborate with the Department of Environment and the Department of Energy to gain maximum control and efficiency over the future resilience of their city. All environmental issues should be assessed in their entirety, as actions can complement or maladapt one another. It is also recommended that the DoURP work closely together with the Department of Environment which has abundant environmental information and experience with SEAs. As there may be no time or budget for a complete SEA of the DoURPs new development plan, this collaboration could help prevent unpleasant surprises regarding environmental issues.

The modelling results show that an increase in evaporative surface cover, and a decrease in building mass per m^2, can drastically reduce the surface temperature. However, it has to be noted that a trade off exists between increasing urban green space to mitigate heat and increasing the water use in order to maintain the vegetation in hot weather (House-Peters and Chang, 2011). Also, the inhabitants who are building their houses tend to choose the cheap and well-recognised materials, for example the popular cement stones. The properties of these building materials are not properly known, and inhabitants should be guided to smart materials by the DoURP.

This study leaves open to discussion the plausibility of an increased surface cover percentage of vegetation and water in already dense areas. However, the surface cover turned into evaporative surfaces in this study, was mainly reappropriated from bare soil or gravel, and some freed-up area available by creating a less dense city. Therefore, for the purpose of this project it is assumed that increasing the percentage of vegetation is reasonable. Other innovations, such as vertical green areas on walls or green roofs, roof-top gardening etc could also have a role to play.

7.4 Discussion of SEA as Framework

The difficulty with integrating urban climatology into urban planning lies in incorporating this into every day municipal practices, urban climate knowledge needs to be paired with policy and regulatory application. Advantages of SEA include the early application which can influence the type of projects planned as opposed to details being altered in a later stage. This makes a tiering of the SEA results possible, for example across to EIA, which is often cost saving. Impacts can also be assessed for the cumulative and synergistic effect of several projects combined, this is a factor often overlooked when conducting assessments for single projects. It is possible to look at larger scale environmental impacts such as biodiversity or global warming. Other advantages which are not directly coupled to the environment but are more of a side effect, namely the consideration of alternatives at an earlier stage. SEA facilitates public participation and also creates a more transparent and robust decision making process. The drawbacks for SEA as for many other models, are the investment of time and resources required.

An important part of the SEA methodology is public participation. In this study public participation has not been actively involved although the urban planners in the area are actively trying to engage the public through questionnaires, workshops and other activities. Participatory urban planning processes have been gaining popularity as a means to advance the rights of those urban citizens who are most vulnerable to climate change (Broto et al., 2014), however it needs to be considered that some informative campaigns might be necessary as some residents may not be familiar with the terminology of global warming.

7.5 Discussion of the Delimitations

The study is limited to the context of tropical Africa, and the fact that Zanzibar is a small island in the Indian ocean makes it even more specific. However, the conclusions are quite broad and can easily be adapted to other contexts. The fact that the planning context in Zanzibar was established relatively recently, the DoURP was founded in 2011, provides great potential to establishing good practices now in the early phases, instead of trying to change set routines later on.

While only surface temperatures were considered as indicator for human thermal comfort, other variables such as humidity, wind and air temperatures are discussed here. The humidity is directly related to the surface temperature and available vegetation and is therefore addressed by this approach. Wind is influenced by the layout of the streets and buildings which are planned at different levels (Hidalgo et al., 2008). At the comprehensive planning stage, to which this research belongs, a vital aspect to be considered is the layout of streets, as their direction, length and width regulates the flow of air through the urban plan. While this has a huge bearing on surface temperature, it is deemed beyond the scope of this study that is based on the SEB. Building layout on the other hand is planned at a detailed level, where modelling wind tunnels could be a valid method for inclusion of human thermal comfort. Air temperature has not been directly considered, however, as it depends on the surface temperature, the wind and humidity, it has been considered indirectly. Thus it could be used as an indicator for the aggregated effect of several approaches that consider different variables.

Important for creating a climate resilient city, in an area with rain seasons, is of course also the surface water run-off, i.e. how much water runs along the areas during a down pour and if this creates problems or risks of flooding and damage. This has not been modelled here but should also be taken into consideration. While this study mainly recommends an increase of vegetative areas, it is posited that such a recommendation may inadvertently help to regulate problems associated with water run-off due to an increase in water absorption by a surface area made more stable by vegetative cover.

Regarding the approach of using SEA as framework, it can be said that it would have been optimal to perform an entire SEA for the study area, especially as large parts of the environmental baseline have been gathered in the Zanplan report (Government of Zanzibar, 2014). Limiting the SEA to only include some aspects of urban climatology, and one approach to climate change adaptation was necessary for the time frame to be reasonable. The importance of synergies between different environmental issues in SEA, such as between climate change adaptation and mitigation, or between climate change and other environmental concerns is emphasised greatly (Larsen et al., 2012). The results are however of great interest for urban planners in an early stage of strategic actions and therefore carry potential to be integrated into a full SEA.

8 Conclusions

In this chapter some conclusions are presented that can be reached through the work of this study.

From the outline of the baseline in this study it can clearly be stated that Zanzibar needs to adapt to climate change. Heat hazards are becoming a serious problem and the inhabitants are today not well equipped for handling these. They need guidance and regulation when it comes to making decisions, and in general an increased knowledge regarding climate change adaptation amongst the population is needed.

The study area needs a formal land use plan that the inhabitants can relate to and rely on, and this plan needs to effectively integrate several aspects of climate change mitigation and adaptation. When it comes to integrating the surface temperatures, and with them the air temperature it can be said that the STAR tool model worked in this context and was an appropriate choice for the situation at hand.

The changes in surface temperatures modelled in this report are considerably large. The increase in surface temperatures caused by global warming is smaller than the decrease of surface temperatures in the best case scenario. The increase in surface temperatures modelled in the worst case scenario is much larger than the increase modelled to be caused by global warming. This can provide a rough guideline to urban planners at an early stage of decision making as to which low-key, no-regret climate change adaptation measures could contribute to making a city more resilient to climate change. It also leads us to the general conclusion that the knowledge of urban climatology can indeed be a major contribution to climate change adaptation.

The urban climate model was integrated into an urban planning procedure in a relatively simple way in the early stages. It was also able to provide general guidelines as to how the surface composition of different land uses ought to look in order to decrease surface temperatures. The model however needs to be verified with actual measured temperatures and measured changes of these.

Using the urban climate model in the framework of an SEA worked very well, and the research points in the direction that it could be a good choice for future studies. It needs however to be verified by performing case studies that perform full SEA's as well as by assessing SEA's that have used the methodology. There are indications toward SEA performing well in the context of African countries and perhaps the use and implementation of the assessment tool should be further pushed for by developed countries. The tool integrates many aspects of sustainability while being adaptable to very distinct contexts, which makes it an appropriate tool for use also in developing countries.

The main conclusion that can be drawn from the results of the modelling in the case study is that the vegetative fraction in all areas of the city is extremely important for lowering surface temperatures. It is not enough to have separate parks, as all UMT categories need to have a certain percentage of green surface cover, especially roads and residential areas. Water could also be used for this, in a traditional way such as fountains, but more modern and innovative uses could be found. Decorative containers could for example line the edges of squares and gather rain water during the wet season. This water could then be filtered and used for an irrigation system to provide for the increased vegetation in the area. In general it could be beneficial to store and make more use of rain water instead of seeing it as a potential hazard. This is done to some extent in the study area in informal ways, but could benefit from a more formal approach.

Beside the vegetation and water, the building fraction and building mass are also extremely important, as they influence how much heat can be stored during the day and released during the night. Currently, cheap imported building materials are used such as corrugated iron roof sheets or cement blocks. The climatological characteristics of these have not been analysed and assessed, however, measured temperatures in housing suggests that these materials are not very well suited to the climate. Houses remain hot throughout the entire night presumably through the release of heat from the building materials and the lack of ventilation. The use of materials in the wide-spread informal housing areas certainly needs to be given some thought, and alternative materials need to be found.

In conclusion it can be said that there are available urban climate models out there for integration into urban planning. The integration into the planning process is possible through tools such as SEA. And finally, the use of urban climate knowledge carries great potential for climate change adaptation and for creating safer cities.

9 Recommendations to the DoURP

The main, general finding this research contributes is the need for a high percentage of evaporative areas in all land use and land cover categories. Small parks and sports grounds spread throughout the entire study area, especially in the dense residential areas, could make a big difference. This not only lowers the surface temperatures, it also provides recreational areas close to peoples homes, which provides incentive to live in a climate smart way, i.e. not to travel long distances to recreational facilities in the heat and in vehicles which emit greenhouse gases.

In order to accommodate the trade-off of increased water use through an increase in vegetation, it is recommended to build rainwater collection facilities, for example in the form of fountains. These cool the air and the surface temperatures, beautify the city, and can be used for watering plants and gardens.

The trend of rising minimum temperatures seen on the Island needs to be kept under observation, as it is already considerably warm in dwellings during the night time. When under heat stress it is important for the human body to regenerate during a cooler night. Solving this through the use of fans or air conditioning will increase the energy use and contribute to yet higher climate change predictions. Relations such as this explain why the importance of synergies between different environmental issues in SEA, such as between climate change adaptation and mitigation, or between climate change and other environmental concerns is emphasised greatly (Larsen et al., 2012). In addition it is not a reliable method approach as many regions in developing countries bear the drawback of ongoing power shortages and outages.

To address the importance of synergies between climate change adaptation and mitigation (Larsen et al., 2012) it is recommended that the DoURP collaborate with the Department of Environment and the Department of Energy to gain maximum control and efficiency over the future resilience of their city. As all environmental issues should be assessed together, as actions can complement or maladapt one other, it is also recommended that the DoURP work closely together with the Department of Environment which has abundant environmental information and experience with SEAs. As there may be no time or budget for a complete SEA of the DoURPs new development plan, this collaboration could help prevent and mitigate unforeseen environmental consequences.

The temperature of residential areas depends on the density and availability of evaporative areas. It is recommended that the DoURP try to gain access to small plots of land throughout the study area and turn these into small parks and green areas. Inhabitants should also be encouraged to maintain vegetation around their houses in the form of grass, vegetable gardens, flowers or shrubs. It is of high importance to plant trees between the houses in the entire area of Ng'ambo. These will provide shade, cool the air through evaporation and prevent soil erosion. Trees will act as natural water retainers during the rainy season provides a dense soil suitable for planting, this will also lead to a reduction of dust in the air during windy weather.

It is recommended that the DoURP implements regulations managing the percentage of evaporative surface in residential areas, as this was shown to have a large effect on the surface temperatures in the city. It is further recommended that this is done in connection with public awareness campaigns which encourage a green Ng'ambo and involve the inhabitants. Other options could be economical incentives such as providing some services to neighbourhoods that manage to sustain their gardens and trees, perhaps these neighbourhoods would have their rubbish picked up regularly or could receive solar cookers. This could be combined with a foreign-funded assistance project. Legislation banning activities that endanger vegetation are an option, but might not encourage public participation or build a pride amongst the inhabitants of a beautiful neighbourhood. Finally, it could also be beneficial to gain control of existing open space in the area and to ensure that these areas are kept open, and that more open spaces are created in the long term.

Most importantly to ensure the safety of the inhabitants during temperature crisis, access to cool areas very close to their homes is vital. A first alternative for achieving this might be the multi-use of space. Open vegetated areas already existent, for example adjacent to governmental buildings, could be turned into beautiful parks with access for the public during office hours. This land is already owned by the government, consists to a large extent of vegetation, and is also to a large extent often unused informally. This could be of great benefit for the study area if managed appropriately.

9.1 Further Issues To Consider in Ng'ambo

There are several factors which influence the urban climate, and can be directly addressed by urban planning, that have not been addressed in this report. This includes the sky view factor. As the height of buildings is increased the sky view factor becomes increasingly important to consider, compared to building mass and density, as it has a large influence on reflection and trapping of radiation. This has not been considered in this study as it needs to be considered on a smaller, more detailed planning level. The same applies to street directions, that have an impact on the channelling of air (Hidalgo et al., 2008), and can affect air temperatures considerably.

The trend of rising minimum temperatures seen in figure 11 could cause increased heat stress and have an impact on human health. Usually the coldest times are during the night, and if the temperature during nights increases the body cannot regenerate from the heat stress experienced during the day. To prevent this, alternative building materials should be considered, and a study should be performed on which local materials have suitable climatic properties. Perhaps there is a possibility of combining existing local materials to create a new material with better climatic properties. The inhabitants should then actively be encouraged to use these when building to create housing that provides better protection from the hot climate. The use of cheap imported materials could be a source of decreased living conditions and might need to be regulated.

Regarding the issue of climate change adaptation, temperatures are only one aspect to be considered. Very important is also the surface water run-off, especially when urban plans are being developed, as new urban development tends to worsen the drainage (Larsen et al., 2012). The STAR tool model used in this study, also offers a similar model for surface water run-off modelling. It is recommended that the scenarios defined in this report, or similar ones, be studied with the surface run-off tool to provide further insight into a climate resilient Zanzibar.

10 Recommendations for Further Research

The main gap in research as observed by this study is the verification of available urban climatology models. Many models are available, but how valid the actual results are is difficult to anticipate. This, combined with the uncertainty of climate change projections, creates quite a high degree of uncertainty. The results from the models need to be verified in multiple broad and narrow studies.

Further research could also be conducted within the topic of SEA's and their use for the environmental issues of urban climatology and climate change adaptation. Both case studies that use SEA's are needed as well as analyses of already performed SEA's and their results.

As already mentioned building materials in tropical Africa and their characteristics is a topic that needs looking into. Perhaps local materials could in simple ways be improved in order to provide better protection for the inhabitants.

11 Closing Remarks

The aim of this study was to find a functioning urban climate model, and to see if the knowledge of urban climatology, through the use of this model, could be integrated into an urban planning context in a developing country. In this respect it has to be said that the study has been successful. The urban climate can indeed be affected by urban planning to extents larger than the predicted climate change, and simple models out there are available to predict this. However, it is important to remain humble and to acknowledge the fact that there are many aspects to be integrated into urban planning and economic assets for few of them. In addition these results need to be thoroughly verified. Nonetheless, the author hopes to have made a small contribution to the field and that further research will be made in this direction.

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List of Figures

If not otherwise indicated all photographs, images and graphs stem from author.

List of Tables

A Appendix

Input parameters used for the STAR tool calculations used for scenario 1 can be seen in figure 27 below:

Row Labels	Built-up Area	Road	Impervious	Vegetation & Water	Bare soil & gravel	ST 1981-2000	ST 2020-2051	Building mass
Beach			7%	37%	56%	38.8	37.5	652
Bus Terminal	18%	3%	43%	20%	16%	44	43.8	2005
Bushland			10%	80%	10%	28.7	29.1	652
Cemeteries	1%	1%	8%	56%	34%	32.9	33.2	1180
Government	12%	0%	10%	50%	28%	33.9	34.2	2005
Major roads	5%	50%	5%	28%	12%	41.9	40.8	4478
Mangrove	1%	1%	10%	80%	8%	28.7	29.1	652
Market	48%	5%	20%	10%	17%	47.6	47.7	1180
Marsh/swamp	1%	1%	7%	65%	26%	31.1	31.4	652
Mixed forest			7%	90%	3%	27.5	27.9	652
Modern low rise	40%	5%	5%	36%	14%	36.5	35.8	2005
Modern mid rise	30%	5%	15%	36%	14%	32.8	32.4	4478
Other impervious	5%	10%	60%	24%	1%	44.3	43.5	2005
Other open space	5%		3%	62%	30%	31.6	32	1180
Park	2%		9%	78%	11%	27.5	27.9	1180
Religion	70%		10%	12%	8%	40.7	40.9	2005
Riverine	1%	1%	9%	63%	26%	31.4	31.8	652
Rural villa	30%	0%	10%	50%	10%	32.6	33	2005
School	10%		20%	60%	10%	31.7	32.1	2005
Sports ground	3%	1%	10%	77%	9%	29.1	29.5	1180
Traditional residentia	70%		10%	12%	8%	45.2	45.05	652

FIGURE 27: Input parameters as specified for scenario 1 of this study for input into the STAR tool model.

A.1 Calculation of the Building Mass

A.1.1 Traditional Residential

Building mass type 2 ground floor and roof: 650 ($\mathrm{kg\,m^{-2}}$) Per extra storey: 620 ($\mathrm{kg\,m^{-2}}$)

House width	House length	House area							
11	15	165							
Description	Material	Surface area	Width	Length	Height	Density (kg/m3)	Total volume (m3)	Total mass (kg)	Mass/area (kg/m2)
Slabs	Coral rag, cement		11	15	0.15	2231	24.75	55217.25	334.65
Cement screed	Cement, sand		11	15	0.015	1578	2.475	3905.55	23.67
Floor beams	Mangrove	0.007162		52		890	0.37242244	331.4559716	2.00882407
Corrugated iron			11	15	1	5	165	825	5
Roof beams	Mangrove	0.007162		52		890	0.37242244	331.4559716	2.00882407
Slabs	Coral rag, lime mortar		0.15	52	3	1920	23.4	44928	272.2909091
Plaster	Lime plaster		0.015	52	3	849	2.34	1986.66	12.04036364
							Total:	107525.3719	651.6689209

FIGURE 28: Example of building mass calculation for building type 2, classic swahili house of coral stone.

A.1.2 Modern Buildings

Building mass type 1 ground floor and roof: 1180 ($\mathrm{kg\,m^{-2}}$) Per extra storey: 820 ($\mathrm{kg\,m^{-2}}$)

Modern 1 storey

Element	Description	Material		Width	Length	Height	Density (kg/m3)	Total volume (m3)	Total mass (kg)	Mass/area (kg/m2)	Reference
Floor	Concrete slab	Reinforced concrete		15	20	0.15	2371	45	106695	355.65	http://www.simetric.co.uk/si_materials.htm
Roof	Concrete slab			15	20	0.15	2371	45	106695	355.65	
Walls	Reinforced concrete	Reinforced concrete		0.3	17.5	3	2371	15.75	37343.25	124.4775	http://www.simetric.co.uk/si_materials.htm
	Blocks	Concrete		0.3	70	3	1640	63	103320	344.4	http://www.simetric.co.uk/si_materials.htm
Total								Total:	354053.25	1180.1775	

Modern extra storey

Element	Description	Material		Width	Length	Height	Density (kg/m3)	Total volume (m3)	Total mass (kg)	Mass/area (kg/m2)	Reference
Roof	Concrete slab		0	15	20	0.15	2371	45	106695	355.65	http://www.simetric.co.uk/si_materials.htm
Walls	Reinforced concrete frame	Reinforced concrete		0.3	17.5	3	2371	15.75	37343.25	124.4775	http://www.simetric.co.uk/si_materials.htm
	Blocks	Concrete		0.3	70	3	1640	63	103320	344.4	http://www.simetric.co.uk/si_materials.htm
								Total:	247358.25	824.5275	

Swahili 1 storey

Element	Description	Material	Width	Length	Height	Density	Total volume	Total mass	Mass/area	Reference
Floor	Slabs	Coral rag,	11	15	0.15	2231	24.75	55217.25	334.65	http://www.simetric.co.uk/si_mat
	Cement screed	Cement, sand	11	15	0.015	1578	2.475	3905.55	23.67	

	Floor beams	Mangrove		52		890	0.37242244	331.45597	2.0088241	http://www.jkuat.ac.ke/departments/civil/wp-content/uploads/2013/10/1.PHYSICAL_AND_MECHANICAL_PROPERTIES_OF_MANGROVE_-Getview-manguriuoyawa.pdf
Roof	Corrugated		11	15	1	5	165	825	5	
	Roof beams	Mangrove		52		890	0.37242244	331.45597	2.0088241	http://www.jkuat.ac.ke/departments/civil/wp-content/uploads/2013/10/1.PHYSICAL_AND_MECHANICAL_PROPER
Walls	Slabs	Coral rag, lime mortar	0.15	52	3	1920	23.4	44928	272.29091	http://www.simetric.co.uk/si_materials.htm
	Plaster	Lime plaster	0.015	52	3	849	2.34	1986.66	12.040364	http://www.simetric.co.uk/si_materials.htm
Total							Total:	107525.37	651.66892	

Swahili extra storey

Element	Description	Material	Width	Length	Height	Density	Total volume	Total mass	Mass/area	Reference
Ceiling	Coral rag slabs	Coral rag, cement mortar	11	15	0.15	2231	24.75	55217.25	334.65	http://www.simetric.co.uk/si_materials.htm
	Roof beams	Mangrove	0	52	0	890	0.37242244	331.45597	2.0088241	http://www.jkuat.ac.ke/departments/civil/wp-content/uploads/2013/10/1.PHYSICAL_AND_MECHANICAL_PROPERTIES_OF_MANGROVE_-Getview-manguriuoyawa.pdf
Walls	Slabs	Coral rag, lime mortar	0.15	52	3	1920	23.4	44928	272.29091	http://www.simetric.co.uk/si_materials.htm
	Plaster	Lime plaster	0.015	52	3	849	2.34	1986.66	12.040364	http://www.simetric.co.uk/si_materials.htm
							Total:	102463.37	620.9901	

A.2 Calculation of the Major Road Mass and Other Impervious Mass

The major road mass and other impervious mass can be seen in table figure 29 below. Only the top two layers of the hard-made surfaces were accounted for as these are deemed to affect the exchange of radiation at the surface.

FIGURE 29: Calculation of road mass and impervious mass adapted from (Cavan et al., 2014).

Road layer	**Major roads**	**Other impervious**
Surface: Wearing & binder course / surfacing	Asphalt concrete 5 cm - 116 kg/m²	Bituminous seal 1 cm - 46 kg/m²
Base: Gravel wearing course	Gravel 15 cm - 246 kg/m²	Gravel 15 cm - 246 kg/m²
Sub-Base: Structural layer / improved sub-grade	Gravel 30 cm	Gravel 30 cm
Sub-grade	Soil	Soil
Total mass	**362 kg/m²**	**292 kg/m²**