High Resolution Heat Stress over a Sahelian City: Present and Future Impact Assessment and Urban Green Effectiveness

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Keywords	Heat stress, urban climate model, urban growth, meter-scale, UrbClim, Niamey, Sahel, climate change
City Population	1,400,000
City Area	556 km^2
City GDP	4.2 billion USD
Climate Zone	BSh (hot semi-arid)
ARC3.3 Linkage	Urban Climate Science

Introduction. Cities are typically warmer than the areas around them, which is known as the 'urban heat island' effect. This means that people living in cities often face higher levels of heat stress compared to those living in nearby rural areas. Additionally, climate predictions suggest that heat waves will become more frequent, intense, and longer-lasting. In the Sahel region, temperatures are rising 1.5 times faster than the global average, creating added challenges for the local populations. Within countries of the Sahel region, an extra one billion people are expected to live in cities by 2050 compared to the present. Many of these cities are already grappling with high heat stress, especially in densely populated informal settlements with inadequate housing conditions. This rapid urbanization, coupled with climate change, is anticipated to significantly increase the exposure to heat stress, posing a substantial risk to public health and well-being. Our analysis aimed to achieve two key objectives. First, we projected the future impact of urban growth and climate in Niamey. Second, we conducted an analysis of how the future climate would affect the socio-economic aspects of the region.

Brief History and Context. In the early 2000s, disaster risk management underwent a significant shift in focus. While increased attention was given to addressing the impact of floods, seismic risks, and landslides, the threat of heatwaves remained largely in the shadows (Harrington & Otto, 2020). Often described as a "hidden hazard," heatwaves had subtle yet profound effects on society, causing underreported human mortality, reduced economic productivity, and higher infrastructure expenses (Wilby, 2008; Whitehead et al., 2009). Unlike more visible disasters, the complexities of quantifying heatwave impacts presented unique challenges, resulting in a lack of comprehensive statistics and underestimation of the problem's true magnitude (Harrington & Otto, 2020).

Moreover, regions accustomed to high temperatures, such as the Sahel, often downplayed the significance of a slight increase in heat, assuming a long history of acclimatization. This led to insufficient attention from governments and weather services, evidenced by the absence of heat action plans and official statistics on heat-related deaths. As a consequence, the full extent of the issue's impact on the local population remained elusive. Acknowledging the increasing concerns associated with heatwaves, extreme heat, and their far-reaching impacts has become essential. This recognition is crucial for the betterment of public health, increased productivity, and the overall well-being of society.

Analysis, Evaluation, and Implementation

Modeling Approach. VITO's research center undertook two projects to assess current and future climate and heat stress levels in Niamey, Niger. Addressing the lack of climate projections at the urban scale, they utilized UrbClim, an innovative urban climate model renowned for its high resolution of 200 meters, which has been successfully validated in various global cities, with very good accuracy (De Ridder et al., 2015). To assess future climate changes, we combined UrbClim with Global Climate Models (GCMs) from the CMIP5 archive of the Intergovernmental Panel on Climate Change (IPCC). They also employed GeoDynamix to model urban growth and derive crucial climate statistics (Crols, 2017). These models conducted simulations for both present-day (2000-2020) and future (2040-2060) climate conditions, considering three scenarios (RCP2.5, RCP4.5, RCP8.5).

Cities prioritize improving the thermal comfort of their residents by optimizing the local microclimate. This critical goal hinges on acquiring detailed urban environment data to compare neighborhoods with ample tree coverage and those with fewer trees.

To carry out this assessment, we employed VITO's Hirex model, following Liljegren's (2008) methodology, which allowed for the evaluation of heat stress at an impressive 2-meter scale. In the pursuit of these comparisons, the study concentrated on three specific city districts: Bobiel, Deyzeybon, and Talladje, each chosen for their unique spatial characteristics. Bobiel and Talladje were identified as having less tree coverage compared to Deyzeybon, as visualized in Figure 1.

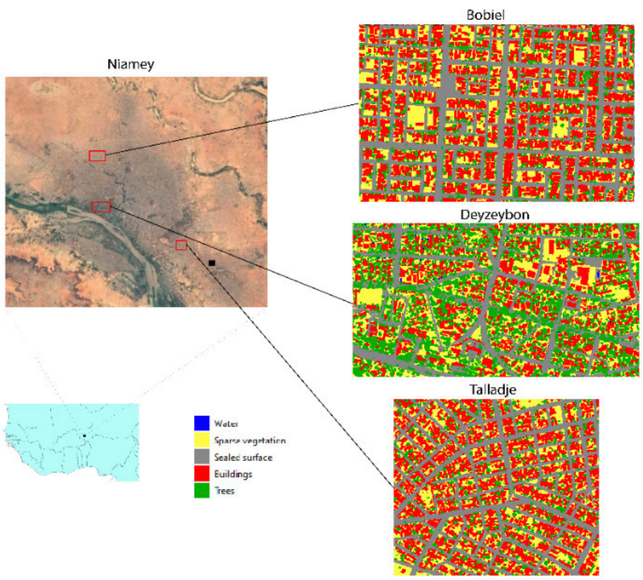

Figure 1. *Location of Niamey in the Sahel region. The meter-scale heat stress modelling domains are indicated in red together with their respective land use.*

Local Scale and Impact of Trees. These findings shed light on the thermal dynamics in Niamey during its hottest months, particularly in March, April, and May of 2020. During these months, temperatures reach their highest points, resulting in elevated levels of heat stress, especially in areas with streets and open paved surfaces. In contrast, areas situated beneath trees experience significantly lower heat stress, typically at least one category lower, and in extreme heat events, this difference can even reach up to two categories lower (>3°C WBGT, see Figure 2).

In addition to the modeling efforts, a practical measurement campaign was conducted in Niamey involving local youth. The results of this campaign revealed a consistent pattern: shaded areas, often created by the presence of trees, consistently displayed lower levels of heat stress compared to their sun-exposed counterparts, with two heat stress categories lower, as shown in Figure 2. This temperature difference was most pronounced during the early afternoon, highlighting the significant cooling effect of trees in alleviating heat stress. Notably, Deyzeybon, with its more dense tree canopy, consistently enjoyed a one-category advantage in terms of lower heat stress when compared to the less-forested districts of Bobiel and Talladje.

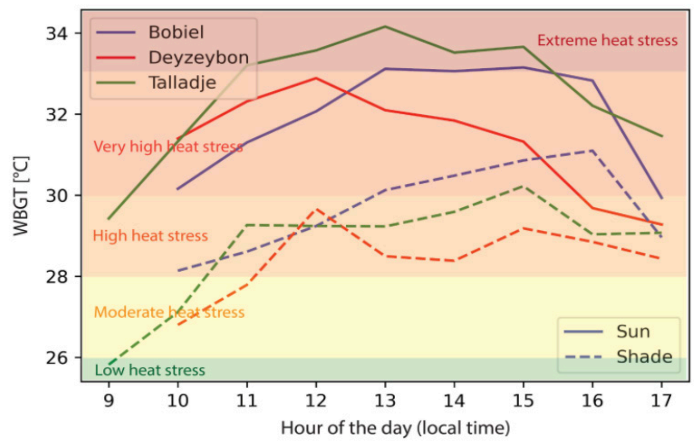

Figure 2. *Wet Bulb Globe Temperature measurements for three locations in sun and shade on 19-05-2022.*

Future Urban Climate. Mid-century climate impact projections for Niamey are available to the public through a user-friendly viewer (https://uclip.marvin.vito.be/uclip). These projections include various climate indicators, with one example shown in Figure 3, focusing on heatwave days. Niamey presently has about 15 annual heatwave days, primarily within the city. However, in future scenarios, this doubles to 30 in the low-emission case (RCP2.6) and triples in the high-emission scenario (RCP8.5). This is also to be seen in the heat stress levels as it reveals that at present, extreme heat stress (WBGT > 33°C) is limited to a few hours and is primarily experienced in direct sunlight, with shade from trees offering relief. However, in future scenarios, the number of hours with extreme heat exposure increases, even in the lowest emission scenario, shaded and under the sunlight areas may face a large increase as shown in Figure 4.

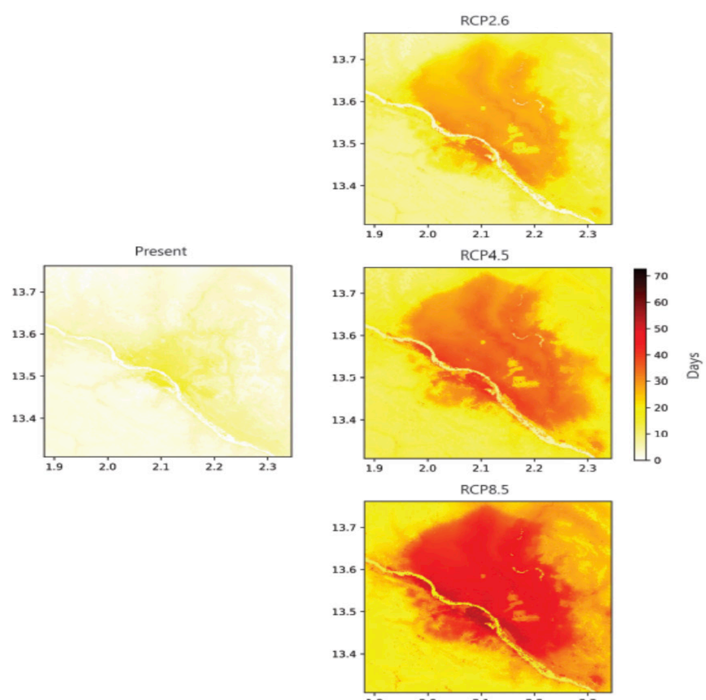

Figure 3. *Number of heatwave days per year over Niamey in the present (2001-2020) and future scenarios (2041-2060).*

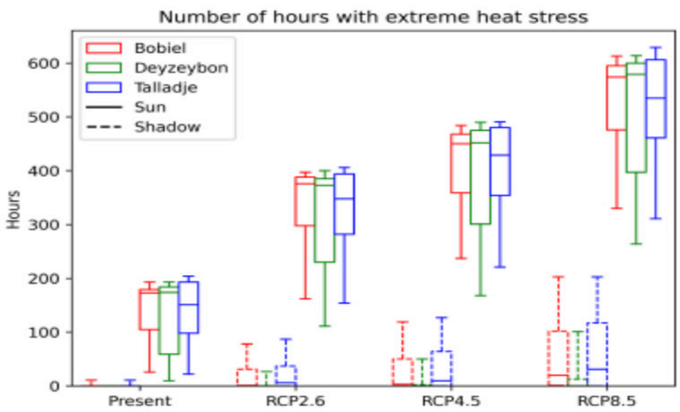

Figure 4. *Number of hours per year with extreme heat stress for present (2001-2020) and future scenarios(2041-2060).*

Socio-Economic Impacts. In the study's final phase, the present and future modeling outputs were employed to assess various socio-economic impacts using established models from the literature. Notably, one of the key findings pertains to the increased mortality rate in Niamey attributed to extreme heat, which was calculated based on log-linear relationships found in literature (WHO, 2014; Gasparrini et al., 2015). Based on the future climate of Niamey, the projections indicate a potential rise in mortality rates for the city, ranging from 1.5% to 2.5% in an average estimation, and up to 5% in a high estimation, particularly in the worst emission scenario, as shown in Figure 5.

Furthermore, when evaluating the reduction in working capacity due to heat stress, the results underscore a substantial impact. In the high-emission scenario, the number of Lost Working Hours (LWH) for moderate activities nearly doubles, irrespective of whether individuals work in shaded or sun-exposed areas as shown in Figure 5. This loss of working productivity is expected to significantly affect the country's Gross Domestic Product (GDP). Turning to the average estimation of GDP decrease per capita (Burke et al., 2015), the study reveals a projected reduction of 2% to 3.5% by the year 2050. However, adopting a high estimation approach intensifies this decline, with values reaching up to 9%, contingent upon the climate scenario considered. These findings underscore the substantial socio-economic consequences associated with the escalating heat stress in Niamey as shown in Figure 6.

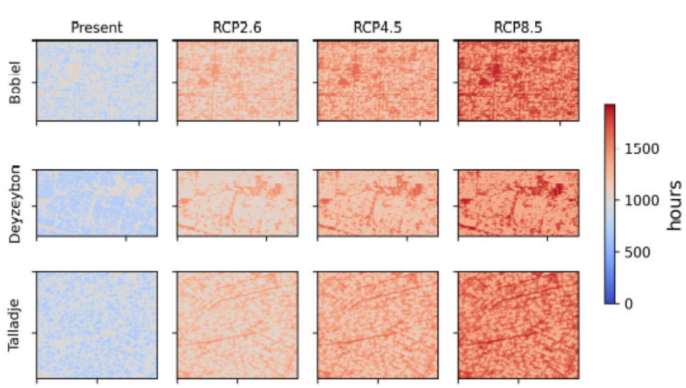

Figure 5. *Number of lost working hours (LWH) per year for moderate activities for present (2001-2020) and future scenarios (2041-2060).*

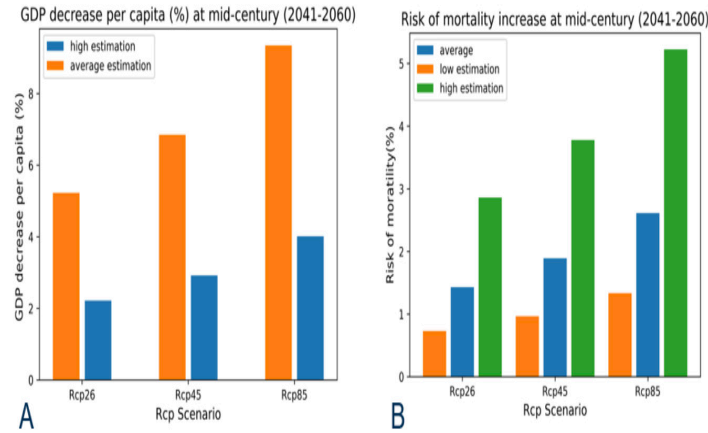

Figure 6. *Socio-economic impacts of climate change in the city of Niamey in future scenarios (2041-2060).*

Future Implementation and Concluding Thoughts. Our approach in this study faced several methodological challenges. The foremost issue was the scarcity of data for Niamey. To create meter-scale heat stress maps, we needed high-resolution land cover and height maps, which were unavailable. Consequently, we had to manually digitize three neighborhoods for modeling. Moreover, the validation process was hampered by the limited number of reference weather stations. We could only access one weather station near Niamey's airport, which isn't the most representative location for comparing urban heat stress due to its low building density and more open spatial structure. Additionally, the available climatic data covered only temperature, omitting crucial variables like humidity and wind speed, limiting our analysis to just two parameters.

Furthermore, our impact calculations rely on relationships and lack detailed information on population statistics and mortality, resulting in some limitations. Despite these challenges, our study offers a replicable framework applicable to different locations and contexts. We hope this research will simulate further exploration of urban heat stress in the region and the implementation of various mitigation strategies. Urban configuration, tree types, and building material characteristics present interesting avenues for policymakers and urban planners. To achieve this, access to more detailed regional data is crucial for a better understanding of local initiatives and challenges. Engaging citizens in the Sahel region in meteorological measurements and involving them in local heat stress adaptation and mitigation plans could be particularly valuable.

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Acknowledgments

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Additional Data

- **Population Density:** 2,500 people/km^2
- **Gross National Income (GNI):** 620 USD (Low Income)
- **Gini Coefficient:** 32.9
- **Human Development Index (HDI):** 0.394 (Low)
- **Type of Climate Intervention:** Hybrid (Mitigation and Adaptation)
