Heat-Related Climate Change Impacts on a Small Island Developing State (SIDS): A Case Study of Trinidad, W.I.

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Abstract: Small Island Developing States (SIDS) have high levels of vulnerability to climate change due to their inherent physical and socio-economic characteristics. Levels of heat within urban areas in the Caribbean are not well-understood or studied. Consequently, heat-related human health impacts can be underestimated or exaggerated. The main objective of this chapter is to determine the extent of temperature variations in Trinidad. Investigations were conducted regarding the temporal variations in land surface temperatures, heat indices, and projected heat accumulation in Trinidad. Analyses showed that urban regions in Trinidad are prone to experiencing higher temperatures and heat due to dense urban infrastructure that absorbs and radiates greater amounts of heat. Heat Index (HI) analyses showed that there were significant ($p \leq 0.001$) increases in the maximum HI in Trinidad from 1976 to 2015. Projected Heat Accumulation (HA) analyses showed that the western and southwestern regions of Trinidad were most prone to heat risks. These findings suggest significant adverse implications for human and ecological health as well as to the broader socio-economic sectors of Trinidad and Tobago.

1. Introduction

Climate change is considered an issue of major concern globally, and there is even greater concern for disproportionately vulnerable groups such as Small Island Developing States (SIDS) within the Caribbean region. Even though the contribution towards greenhouse gas (GHG) emissions from SIDS is negligible (compared to developed countries), the impacts of climate change can be even more severe due to the inherent physical characteristics of SIDS which make them more vulnerable to multiple climate change stressors (IPCC 2021). Climate change vulnerability and adaptation is variable between the islands in the Caribbean due to the high diversity of physical and human attributes such as geophysical characteristics as well as socio-economic structures (Leal Filho et al. 2021). Recent available projections show that climate change is already affecting the growth and development of SIDS, and further effects are inevitable in the near future. According to the Intergovernmental Panel on Climate Change (IPCC), current and future risk drivers for climate change in SIDS include sea level rise (SLR), tropical cyclones, increasing air and sea surface temperatures, disease prevalence, and changing rainfall patterns (IPCC 2021). The Special Report on Emissions Scenario (SRES A2 and B2) scenarios as well as Representative Concentration Pathway (RCP) models project that there will be increases in temperature across the Caribbean with drier conditions and an increasing frequency of droughts, increased sea level and coastal flooding, as well as increased sea surface temperatures (IPCC 2021).

Trinidad and Tobago is an archipelagic republic in the southern Caribbean, located between the Caribbean Sea and the North Atlantic Ocean. Trinidad is split into 14 regional corporations and municipalities (Figure 1 below).

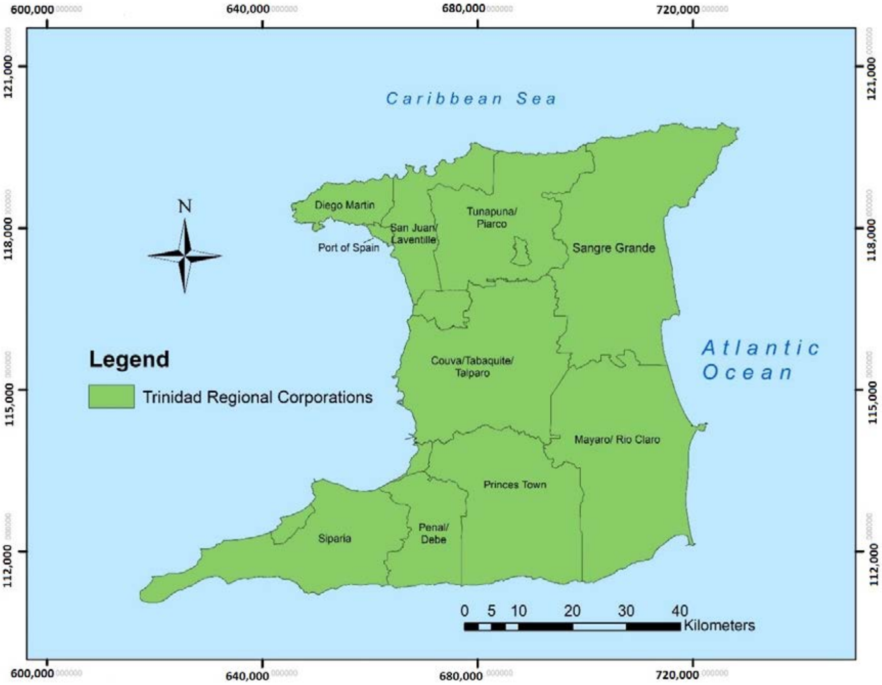


Figure 1. Map of Trinidad. Source: Figure by the authors.

Trinidad is a Caribbean SIDS, and one of the current and future climate-related risk drivers for SIDS is increasing temperatures (both ambient and surface temperatures). This can result in impacts such as a loss of ecosystem services and adaptive capacities, which are essential to lives and livelihoods in many small islands (IPCC 2021). There is a consensus that small islands do not have uniform climate risk profiles due to variations in both the physical and human attributes of each island. In particular, small islands are by no means the same when it comes to physical size, character, or economic development, creating variations in adaptive capacities (IPCC 2021). Therefore, approaches to mitigate and adapt to climate change would differ among these islands, particularly tropical SIDS within the Caribbean. Persons that live and work within highly urbanized regions will also be greatly impacted by increased heat since urban areas trap and retain heat due to the urban heat island effect (Shi et al. 2021). It is therefore imperative that urban populations be targeted for adaptation and mitigation so that relevant precautions can be taken to reduce health impacts in urban areas within Trinidad and the Caribbean region.

Traditionally, heat-related impacts on humans and the environment have only been attributed to increases in temperature, and due to a lack of long-term data, the impact of humidity was often neglected in climate research (Marx et al. 2021). However, in recent years, this has changed with the introduction of various heat stress indications such as the Heat Index, which are now frequently used to determine the effects of heat on human health and to predict heat waves (Dahl et al. 2019).

Increased heat levels are a major cause for concern globally, as most biological life is sensitive to small variations in temperatures and function optimally within a narrow range of temperatures (Alinejad et al. 2020). Threats can be even more pronounced in humid regions such as the Tropics (Matthews 2018). It is therefore crucial that the heat in tropical regions such as the Caribbean should be closely monitored and evaluated in order to prevent and lessen potential negative impacts (Matthews 2018; Di Napoli et al. 2022).

2. Materials and Methods

Three different types of heat data were collected and analysed. These included Landsat thermal imagery, heat index variations, and projected heat accumulation. Descriptions of data collection and analysis for each type of heat data are provided below. Additionally, an impact analysis on various sectors was carried out through a literature review and synthesis and described in the discussion.

On 9 January 2014, 25 January 2014, and 28 January 2015, Landsat thermal infrared data were obtained online from the United States Geologic Survey (USGS) Global Visualization (GloVis) tool. Thermal band 10 was used to create a mosaic of Trinidad at 30 m resolution. These years and days were selected because they were easily available, and the mosaic pictures at the site on those dates were cloud-free, allowing for full visibility of the study areas. The temperature scale on the map was times 100 to eliminate decimal values. Maps were displayed in ArcGIS 10.2.

In order to calculate the heat index (HI), temperature and relative humidity data are needed. The Trinidad and Tobago Meteorological Services (TTMS) is the main meteorological and forecasting facility for Trinidad's weather and is considered the most reliable data source. Therefore, hourly temperature and relative humidity data for this study were acquired from the Trinidad and Tobago Meteorological Services (TTMS). Intermittent data from 1976 to 2015 from the following years were utilized for the study: 1976, 1982, 1986, 1992, 1996, 2002, 2006, 2012, 2014, and 2015. The data consisted of hourly temperatures and relative humidity readings for 24 h days. These data were utilized because they were available and complete datasets for representative years per decade for approximately four decades. This present study confines itself specifically to the changes in maximum HI.

The heat index was calculated using the formula by Rothfusz and NWS Southern Region Headquarters (1990):

$$\mathrm{HI} = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - \\ 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 + 1.22874 \times 10^{-3}T^2R + \\ 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2$$

where T = temperature (°F); R = relative humidity (integer percentage).

The HI was calculated in Fahrenheit and converted to Celsius. The HI calculations were made for every hour of every day for the ten years used in the study. The maximum HI that occurred per day was then determined from the data using the hourly temperature and relative humidity as well as the HI formula. The formula was applied to data for every hour of every day, and the maximum HI per day was obtained. The maximum HI per day was used to calculate the average maximum HI per month and year. Calculations were also made based on seasonal variations. The dry season in Trinidad occurs in the months of January to May, while the wet season occurs from June to December (TTMS 2023).

Statistical analyses were carried out using SPSS version 23. The raw dataset was also examined under quality control measures to remove any erroneous data. The datasets obtained did not contain any missing data. There were also no negative values (which could be an indication of errors).

In order to determine if there were significant changes in maximum HI, statistical analyses were completed to determine significant changes. These included Student's T tests and one-way ANOVA tests as well as additional post hoc Tukey tests, which were used to analyse the data in greater detail.

The Heat Accumulation for Trinidad was calculated and mapped using the SimCLIM Desktop 4.0 degree day site-specific model that calculates degree day based on daily time series of maximum and minimum temperatures. The degree day estimates were then calculated using the area under the diurnal temperature curve and between the thresholds using a double sine estimation method, as shown in Figure 2 below.

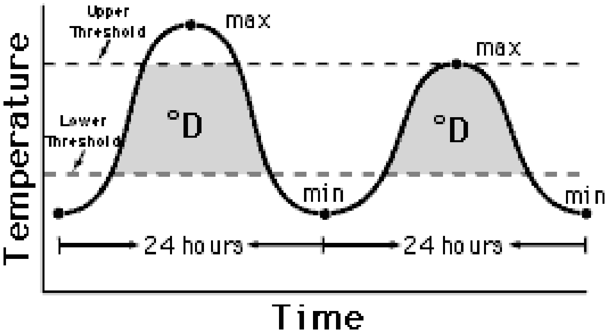


Figure 2. Thresholds and accumulated degree days. Source: Adapted from Wilson and Barnett (1983).

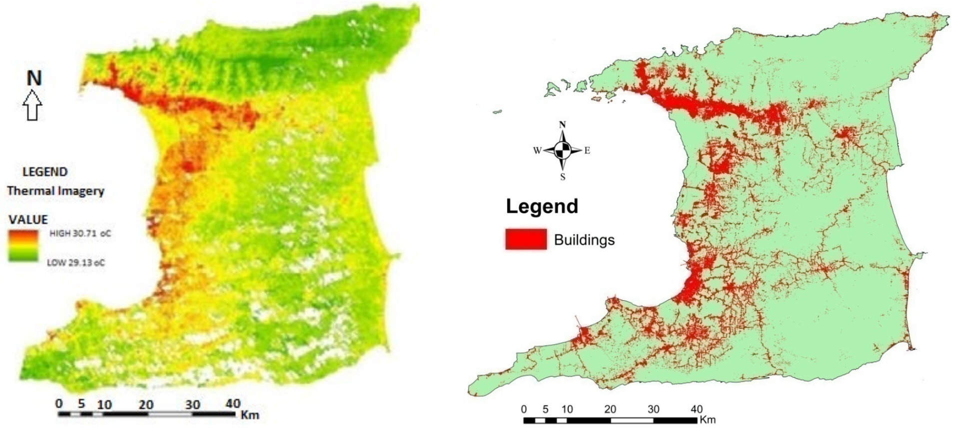
The degree day impact model was visualized for Trinidad using a base temperature of 25 °C. This value was used based on similar average historical temperatures for Trinidad. The degree day impact model was run using the IPCC's four low to high global warming Representative Concentrations Pathways (RCPs) (2.6, 4.5, 6.0, and 8.5) for a time series (2014, 2015, 2016, 2017, 2018, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100). Maps of the years 2014, 2018, 2030, 2050, and 2090 were used for analyses to visualize trends in the heat accumulation based on the highest degree day values. These changes were calculated for each representative concentration pathway (RCP). The representative scale on each map is measured in units of accumulated degree days.

The year 2014 was used as a base for analyses and comparison to future projected changes as this was the earliest year used for analyses. Heat accumulation (HA) was simulated with an ensemble of the same 40 General Circulation Model (GCM) patterns used by the IPCC and applied with high sensitivity. High climate sensitivity was chosen so that corresponding low and high bounds of the climate uncertainty ranges could be accounted for in Trinidad. The median projection of the GCM ensemble was used for each scenario.

3. Results

3.1. Thermal Imagery

Comparative maps were completed using ArcGIS 10.2. The maps in Figure 3 show thermal imagery of Trinidad on the left and the distribution of urban infrastructure on the right.



(a)

(b)

Figure 3. Trinidad (**a**) Landsat thermal imagery; (**b**) distribution of buildings. Source: Authors' compilation based on data from the United States Geologic Survey.

3.2. Heat Index

3.2.1. Heat Index Variations

The average monthly maximum HI for the time period (1976–2015) was calculated using daily maximum HI values (Figure 4). The maximum HIs in August (37.4), September (38.1), and October (38.1) were significantly higher compared to other months ($p \leq 0.001$).

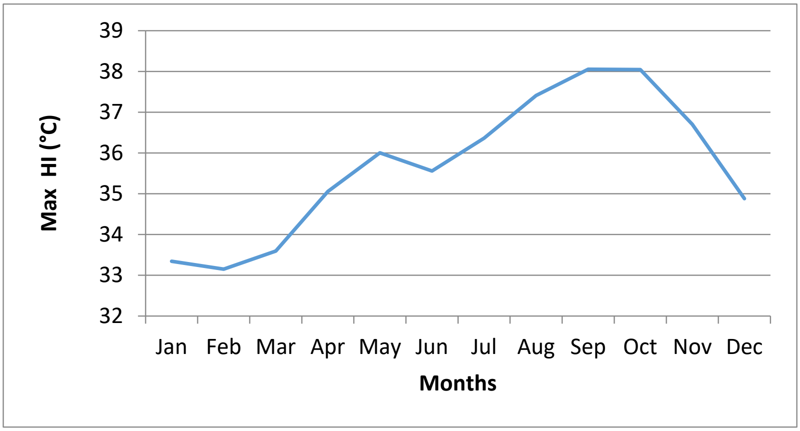


Figure 4. Monthly average maximum HI (1976–2015). Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services.

The average yearly maximum HI for the time period from 1976 to 2015 is shown below in Figure 5. Statistical analyses showed that there was a significant increase ($p \leq 0.001$) in the average maximum HI (from 1976 to 2015).

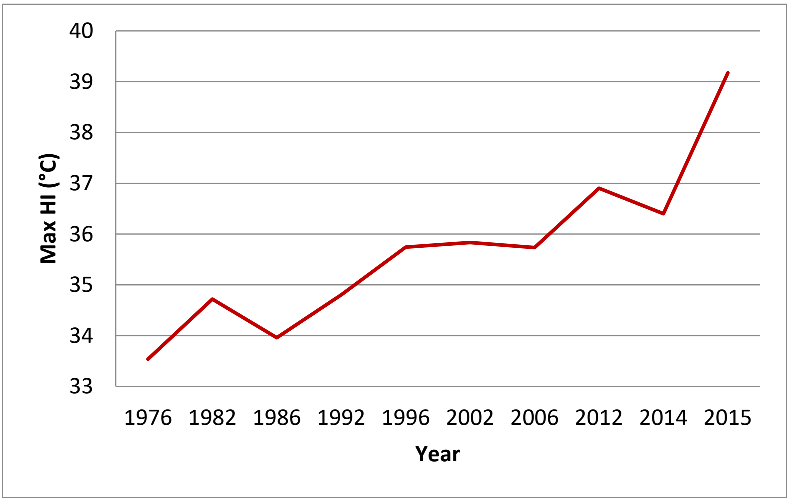


Figure 5. Yearly average maximum heat index (1976–2015). Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services.

3.2.2. Seasonal Variation in Maximum Heat Index

The seasonal variation in the yearly average maximum HI is shown below in Figure 6. The maximum HI was higher in the wet season compared to the dry season. A Mann–Whitney U test was carried out, comparing the average maximum HI during the wet and dry season from 1976 to 2015. The analyses showed that the average maximum HI was significantly higher ($p \leq 0.001$) in the wet season compared to the dry.

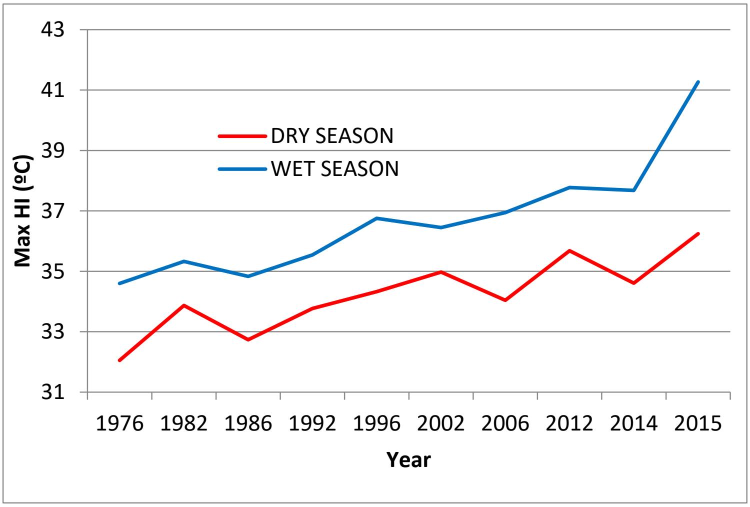


Figure 6. Seasonal variations in average maximum HI (1976–2015). Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services.

3.3. Heat Accumulation

The HA maps for RCP 8.5 show that the areas with the highest HA (purple and deep purple) were again within the western portions of Trinidad. Port of Spain and Diego Martin Regional Corporations were the hottest regions in Trinidad. However, there were even larger areas of the warmest regions (purple and deep purple) in 2090 under RCP 8.5 compared to all other RCPs. The highest HA values were approximately 2319-degree days in 2090 under RCP 8.5 (Figures 7–11 below).

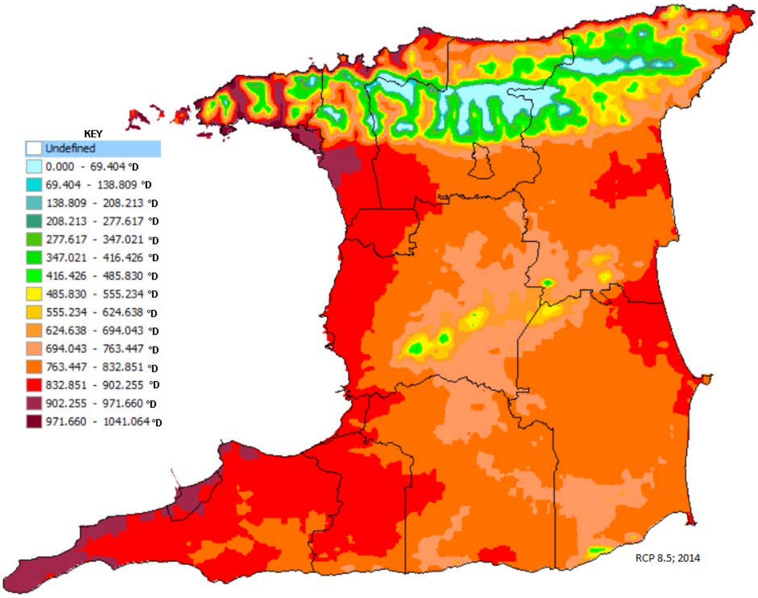


Figure 7. Heat accumulation in Trinidad for RCP 8.5 in 2014. Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services and CLIMsystems Ltd.

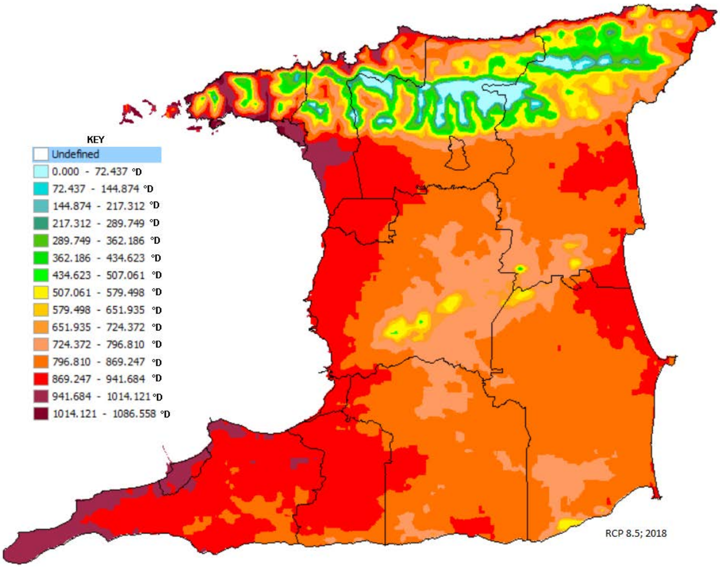


Figure 8. Heat accumulation in Trinidad for RCP 8.5 in 2018. Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services and CLIMsystems Ltd.

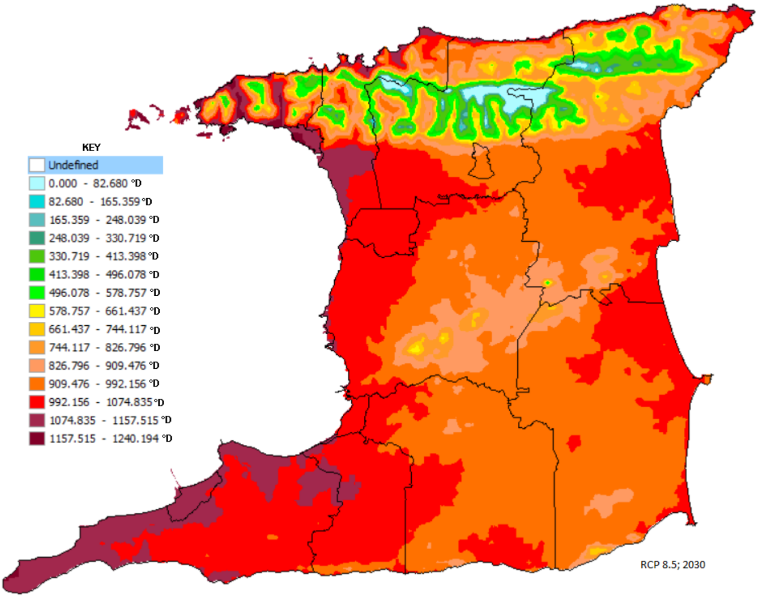


Figure 9. Heat accumulation in Trinidad for RCP 8.5 in 2030. Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services and CLIMsystems Ltd.

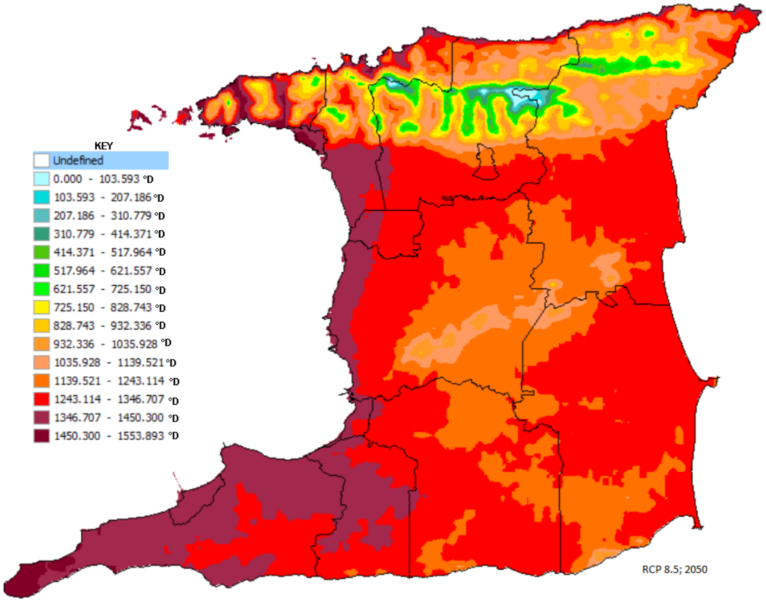


Figure 10. Heat accumulation in Trinidad for RCP 8.5 in 2050. Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services and CLIMsystems Ltd.

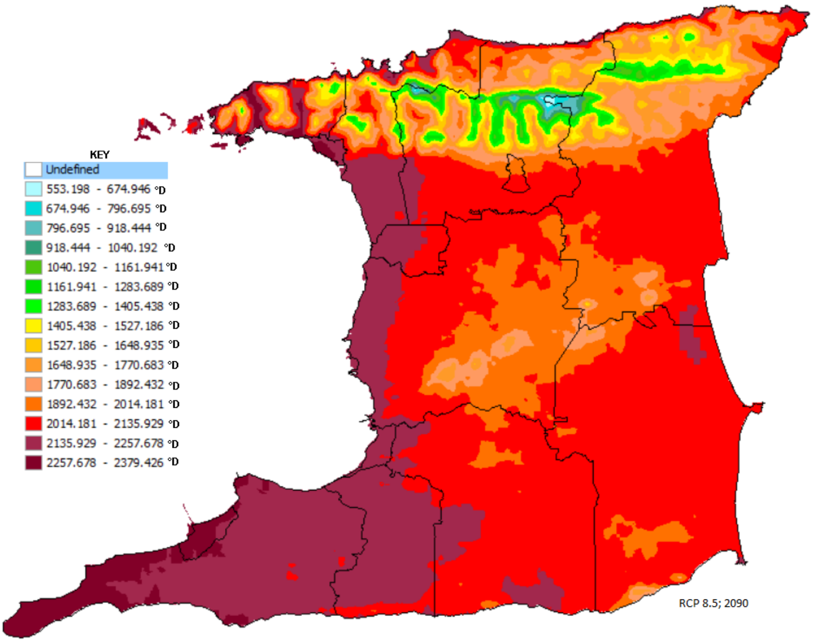


Figure 11. Heat accumulation in Trinidad for RCP 8.5 in 2090. Source: Authors' compilation based on data from the Trinidad and Tobago Meteorological Services and CLIMsystems Ltd.

4. Discussion

4.1. Heat Trends

4.1.1. Land Surface Temperatures

The comparative maps of land surface temperature and urban development in Trinidad show striking similarities in distribution. The hottest regions in Trinidad are demonstrably centred around urbanization. This is a visible indicator that urbanization and urban infrastructure in Trinidad plays a significant role in heat absorption and retention. Landsat thermal imagery showed that the western portions of Trinidad are warmer compared to the surrounding areas. This is indicative of the presence of a surface urban heat island (SUHI) as the urban regions are warmer than the surrounding areas (Figure 3).

The urban environment can be characterized by a conglomeration of anthropogenic surfaces, vegetation, and water features. All of these urban features dictate and influence temperature regimes within the environment and can create a separate microclimate (Le and Tran 2019; Giyasova 2021). Urban areas, particularly those within the tropics, have experienced population movements, urban growth, and industrialization which have led to elevated temperatures and the creation of urban heat islands (UHIs) such as the UHI in San Juan, Puerto Rico (Molina et al. 2020). Similar formations of UHIs are possible within other Caribbean SIDS. Thermal imagery indicated that the majority of the developed western portion of Trinidad is warmer than the rural undeveloped regions in Trinidad. Anthropogenic infrastructure within urban areas can result in increased temperatures due to the increased surface areas of buildings that absorb thermal radiation and reduce wind speeds. The thermal characteristics of urban surface materials allow for increased heat storage and higher heat capacities and conductivities than vegetated surfaces. Urban areas also have vast amounts of impervious surfaces such as asphalt/pitch and concrete that decrease cooling. (Vujovic et al. 2021). Persons living within highly urbanized regions are exposed to greater health risks due to heat stress and heat strokes with most heat mortalities occurring in highly urbanized cities as a result of the urban heat island effect (Heaviside et al. 2017; Piracha and Chaudhary 2022). The most vulnerable groups include the elderly, the very young, the chronically ill or disabled, expectant mothers, and the socially isolated. Low-income and minority groups are also high-risk groups since they lack the social and financial capacity to withstand adverse climatic conditions (Heaviside et al. 2017; Piracha and Chaudhary 2022). It is therefore necessary for accurate temperatures to be disseminated to the general public so that they can undertake the necessary measures and precautions to protect themselves from the health risks and impacts associated with elevated temperatures, particularly in regions of high population densities such as Port of Spain. It is understood that humidity is an important factor in assessing heat-related impacts on human health as well as the quantification of the UHI effect. Therefore, further studies should be conducted inclusive of humidity for heat index and HI effect calculations in order to quantify the heat-related health impacts within urban regions in Trinidad.

4.1.2. Heat Index

The maximum HI in Trinidad has increased significantly from 1976 to 2015, particularly during the wet season. The increasing heat index found in this study was similar to findings in other parts of the Caribbean, including islands in both the Greater and Lesser Antilles, where the HI has notably increased over a 35-year period (Ramirez-Beltran et al. 2017). Additionally, observations in other parts of the Caribbean revealed that the maximum HI was higher during the wet season, similar to the findings in this study (Ramirez-Beltran et al. 2017). Temperatures in Trinidad and Tobago are generally higher during the wet season due to higher levels of humidity (TTMS 2023).

4.1.3. Heat Accumulation

The increase in HA was visually projected to occur mostly in the western portion of Trinidad under all emission scenarios, with southwestern regions being at high risk due to increasing HA. The change in HA was found to be increasing among the various emission scenarios, with the greatest increases occurring under RCP 8.5, which was expected considering RCP 8.5 assumes that GHG emissions would continue to increase throughout the 21st century. This is similar to other studies conducted on HA in Thailand and Pakistan, where RCP 8.5 yielded the greatest increases in HA over projected time periods (Nasim et al. 2018).

The eastern parts of Trinidad also see an increase in HA, but to a lesser extent than the western portion of Trinidad. All scenarios show that the western regions of Trinidad are projected to be some of the most impacted areas, as they are seen to be the hottest regions in all projections. The southwestern portion of Trinidad is also one of the most impacted, with the HA being very high at the southwestern tip of the island, indicating that this region is at high temperature-related climate change risk and vulnerability. The mountainous regions of Trinidad (the northern, central and southern ranges) were some of the coolest regions. All scenarios also show that there would be a decrease in the coolness of these mountainous regions.

There are a few limitations and uncertainties associated with the methods involved in developing SimCLIM. These include the fact that the pattern scaling and downscaling methods used for each region are based on the best available knowledge of that location and available data. Therefore, the values presented should be viewed as best estimates (Li et al. 2017). However, the climate data used within SimCLIM are considered legitimate (according to the IPCC and country-specific standards), wide-ranging (high-resolution data), defensible (scientifically robust), and actionable (Li et al. 2017). This heat accumulation information derived from SimCLIM can therefore be considered fit for adaptation and mitigation planning. Additionally, the maps generated using all four RCPs (emission scenarios) similarly indicate that the western and southwestern portion of Trinidad is at most temperature- and heat-related risk. It is therefore imperative that action is taken within these regions in order to reduce further impacts, which can lead to human morbidity, mortality, and a range of ecological impacts.

This study highlights the western and southwestern regions of Trinidad as being most vulnerable and at risk due to heat related impacts. It is therefore important that adaptation strategies are implemented for these particular regions in order to minimize impacts. The majority of the population of Trinidad resides within the western portion of Trinidad, putting them at high heat-related risk and vulnerability.

4.2. Threats Posed by Extreme Heat

4.2.1. Threats to Human Health

There are a number of occupational health concerns associated with increased heat. Psychomotor, perceptual, and cognitive performances in the workplace are all affected due to increases in heat. These all exacerbate the risk of injuries on the job (Kjellstrom et al. 2016; Borg et al. 2021). There are established standards for workplace heat stress management according to the International Organization for Standardization (ISO) (Parsons 2018). However, according to the Intergovernmental Panel on Climate Change (IPCC), some parts of the world have already notably exceeded the ISO level for safe work activity during the hottest months of the year. As heat increases, job exertion, heat stress, and heat exhaustion also increase, and this reduces the amount of work that can be carried out, particularly by outdoor workers, during the hottest periods of time (Kjellstrom et al. 2016; Parsons et al. 2021). This can potentially reduce the overall productivity of a country and thus affect the economy.

The extreme heat caused by climate change poses significant threats to human health in a myriad of ways. Indirect adverse health effects such as air pollution due to wildfires coupled with direct effects of extreme heat on the human body often lead to morbidity and mortality. These effects tend to disproportionately affect vulnerable populations of society, including, but not limited to, low-income individuals, disabled persons, chronically ill persons, and the elderly. Globally, the negative health impacts of extreme heat have been evident as heat waves in July 2022 affected Europe and the USA, which put stress on societies and increased mortality risk (Nature 2022). One study considered 43 countries during the period 1991–2018 and determined that 37% of "warm-season heat-related deaths" could be attributed to anthropogenic climate change (Vicedo-Cabrera et al. 2021). Furthermore, increased mortality due to climate warming is evident on every continent (Vicedo-Cabrera et al. 2021).

When increased heat leads to wildfires, the subsequent emissions in the smoke produced result in adverse effects to human health and may lead to death through smoke inhalation (Guo et al. 2019). In Trinidad, as discussed previously, there have been wildfire events that exacerbated asthma in students as well as those that caused the death of a 67-year-old man due to smoke inhalation (Felmine 2019).

If the human body is subjected to increased temperatures and is unable to cool itself efficiently, a person may suffer from heat stress with a spectrum of symptoms such as nausea, excessive sweating, headache, muscle cramps, and collapse. Heat stress can be categorized as heat exhaustion, where a person can take measures to cool down; heat injury, where organ damage may occur; or life-threatening heat stroke, where medical assistance is required (Morris and Patel 2021). In 2022, the year's highest recorded temperature in Trinidad was 34.2 °C in Piarco (Hosein 2022). Notably, the threat of heat stress is increased in urbanized areas in Trinidad such as the city of Port of Spain due to the surface urban heat island. Furthermore, there is increased morbidity and mortality among vulnerable groups such as children, older persons, pregnant persons, and disabled persons, as these groups are typically more sensitive to heat. Additionally, due to physical activity, athletes and individuals who work outdoors such as on construction sites are also at higher risk of heat stress.

The observed impacts of climate change include adverse health effects across geographical regions and are largely negative on all scales. Climate change has been positively associated with an increase in illnesses such as dengue, chikungunya, and Lyme disease. Additionally, due to heavy rainfall and flooding events, there are observed increases in vector- and waterborne diseases in affected regions. Furthermore, increased heat due to climate change has resulted in increased respiratory diseases from ozone air pollution, smoke associated with wildfires, and shifting pollen seasons (IPCC 2021). Extreme heat due to climate change has also negatively impacted the mental health, quality of life, cognitive performance, and happiness of individuals who are affected by heatwaves. Climate change has also been observed to contribute to food insecurity through extreme weather and climate events such that populations consume inadequate food. This results in malnutrition, which disproportionately affects children and pregnant women and results in disease susceptibility in low- and middle-income populations (IPCC 2021).

4.2.2. Droughts

Extreme heat levels result in an increased frequency and intensity of droughts which are prolonged periods of abnormally low precipitation leading to water shortages. Droughts can be classified as short-term or long-term. Short-term droughts tend to affect agriculture and result in wildfires, while long-term droughts affect water resources and lead to ecological losses (Gamelin et al. 2022). In recent years, there has been a notable increased propensity of droughts globally, resulting in lowered crop yield, increased food prices, and the lowered production of hydropower (European Commission 2022; Moens 2022).

In Trinidad and Tobago, although drought is a natural phenomenon, it has been noted that droughts have been becoming more severe and less predictable, leading to adverse effects on the water resources and agriculture (Beharry et al. 2019). Trinidad and Tobago experienced notable droughts in 1997–1998 and 2002–2004; however, in 2009–2010, the country experienced a severe, wide-spread drought with rainfall reaching 25% of expected levels. This resulted in a 6.9% increase in food prices, with cattle livestock being affected by disease and two of the reservoirs recording lower than average levels (Beharry et al. 2019).

In 2018–2019, Trinidad and Tobago, along with many other Caribbean nations, was placed on drought watch, with the Water and Sewerage Authority (WASA) advising the public to conserve water due to reduced rainfall levels (Government of the Republic of Trinidad and Tobago 2019). During this time, one of Trinidad and Tobago's largest rice producers noted that due to the lack of water, he was forced to scale back production from 300 acres of rice planted to 10 acres of rice as of January 2019 (Paul 2019). Agricultural Society President Dhano Sookhoo urged the public to prepare for increased food prices and the non-availability of food. Sookhoo also predicted that the country would be driven to import more food that would usually have been grown locally (Paul 2019). According to Kishan Kumarsingh, Head of the Multilateral Environmental Agreements at the Ministry of Planning and Development, these weather extremes experienced in 2018 and 2019 may become the norm as the global temperature increases (Doodnath 2020).

4.2.3. Wildfires

Wildfires are unplanned fires in a natural environment such as forests or grasslands. Since wildfires are driven by dry, organic material that can ignite and burn when heated, the extreme heat, drought and low relative humidity generated by climate change exacerbate this natural phenomenon (UNFCCC 2022). With business-as-usual circumstances, the number of wildfires is expected to increase by 14% by 2030, 30% by 2050, and 50% by 2100 (UNFCCC 2022). Not only does climate change exacerbate wildfires but wildfires exacerbate climate change, creating a positive feedback loop (UNFCCC 2022). The ramifications of wildfires include adverse health effects due to smoke inhalation, the economic burden of rebuilding areas ravaged by wildfires, watershed degradation, soil erosion, and loss of biodiversity (UNFCCC 2022).

Historically, areas throughout Trinidad and Tobago, particularly along roadways and hillsides, have been known to burn during the dry season from January to May (ODPM 2011). However, increased wildfire events have been noted to correspond with periods of drought due to increased heating. In 2019, during a period of drought, a notable wildfire incident occurred in Princes Town near two primary schools, leading to the forced evacuation of over 900 students (de Silva 2019). It was reported that the smoke from the fire affected students with asthma, and a galvanized water line was damaged by the fire and subsequently ruptured (de Silva 2019). In some cases, such as in another wildfire in La Romaine of 2019, the effects have been fatal. A wildfire along Allahar Street resulted in the death of a 67-year-old man and the destruction of his house. According to the autopsy report, he died from smoke inhalation (Felmine 2019). As global temperatures continue to increase, there will be an increased frequency and intensity of droughts and resulting wildfires.

4.2.4. Threats to Ecological Health

Terrestrial ecosystems are negatively affected by extreme heat in different ways, ranging from loss of habitats due to wildfires, dehydration due to lack of rain, increased stress on the organisms involved, and general loss of biodiversity. In Trinidad, when extreme heat causes the degradation of the habitats of wildlife, it leads to the reduction in feeding rates, lower reproductive success, and greater energetic loss (Ratnayake et al. 2019) This can result in the migration of species to species being at risk of extinction and the subsequent loss of biodiversity.

4.2.5. Threats within the Agricultural Sector

The USAID Climate Risk Profile lists agriculture as one of the areas most impacted by climate change in the eastern southern Caribbean (ESC), where Trinidad and Tobago lies. This can be attributed to climate trends observed in the region that can make an already brittle agriculture sector even more fragile (USAID 2021). Heat-related changes of major concern for the sector are temperature patterns and the frequency and duration of natural disasters such as droughts (Makara 2021). Reports have shown that annual temperatures have increased 0.2 °C–0.7 °C, which varies (USAID 2021), and drier dry seasons have been observed in the country (Beharry et al. 2019).

Even though the agriculture sector in Trinidad and Tobago is overshadowed by its energy-driven economy (Oxford Business Group 2020), the effects of climate change will still be felt on the livelihoods of almost 2.9% of the population who are employed in the sector and the contribution of agriculture to the gross domestic product (GDP) of the country (1.1%) (World Bank 2020). Many farmers utilize water from rivers for the irrigation of their crops; therefore, droughts during the months of January to May reduce their ability to do so (Beharry et al. 2019). This can lead to unproductive soils and timing and the reduced yield of crops (USAID 2021). Warmer weather from increased temperatures will result in arid soils, the proliferation of pests and diseases, and further irrigation challenges due to reduced water resources. In order to protect against these livelihood losses, climate risk insurance policies such as the Livelihood Protection Policy (LLP) under the Climate Risk Adaptation and Insurance in the Caribbean (CRAIC) project can be utilized by credit unions and farmers cooperatives (MCII 2020). However, after extreme climatic events such as tropical storms in the Caribbean, insurance premiums will likely rise in the region (Caribbean Development Bank 2020).

However, the combination of changes in temperature, precipitation, and CO_2 concentration have created new levels of agricultural productivity and adaptation in the Caribbean region (Reyer et al. 2017). These regimes may reshape growing days as well as modify the phenology of several crops. Some of the biophysical impacts of climate change can be amplified or mitigated by the management responses of farmers (Banerjee et al. 2021). For example, by 2050, there is expected to be a significant reduction in areas suitable for tomato growing, but alternatives can be used such as cassava, sweet potato, and yam. Additionally, the cocoa crop is expected to be more climate resilient, but precautions should be taken in the form of access to irrigation during more severe dry spells. Furthermore, there is increased climate suitability in the upland areas and surrounding mountain ranges for crops such as banana, cassava, sweet potato, yams, and ginger (Eitzinger et al. 2015).

With regard to the livestock and dairy sector of the country, rising temperatures and humidity can also result in a condition in animals called heat stress, resulting in reduced feed intake, increased risk of diseases, production losses, heat stroke, and even death. Moreover, these conditions will further exacerbate the current unfavourable situation in the dairy industry in the country (Ali et al. 2019). According to farmers, there is a greater predicament to produce milk. This is due to the increase in feed prices, which can be attributed to global shipping costs as the country does not produce corn or grass suited for dairy production (Chaitram 2021).

The reliance on external sources for animal feed is a trend that can also be seen in the food supply for the rest of the country. This is evident in Trinidad and Tobago’s high food import bill of TTD 5 billion, which makes up 18% of the country’s entire imports (World Bank 2021). Furthermore, the country is the second largest exporter of US agricultural products in the English-speaking Caribbean. Domestic agricultural production is limited due to factors such as land space and natural disasters such as droughts and flooding (International Trade Administration 2022). However, agricultural production has recently been on a path to recovery. Inflation in the country is driven by food prices in both international and domestic fluctuations, and therefore, a goal of the National Food Production Action Plan aims to reduce the food inflation rate (Shik et al. 2019).

4.2.6. Threats within the Energy Sector

As global temperatures continue to rise, there has been greater demand for efficient cooling for both comfort and health reasons. Globally, as of 2018, the use of air conditioners and electric fans to stay cool accounted for about 20% of the total electricity used in buildings (International Energy Agency 2018). China saw the greatest and fastest increase in energy use for cooling since 1990, resulting in a 69-fold increase by 2016 with the growth showing no signs of slowing (International Energy Agency 2018). Although these space coolers alleviate the heat, they also paradoxically contribute significantly to further warming, as these alone could cause 0.4 °C of additional warming by the end of the century. This leads to a positive feedback loop where extreme heat necessitates space cooling, while more space cooling results in increased ambient heat.

In Trinidad and Tobago, the demand for cooling is influenced by its proximity to the equator and its average temperature of 26.5 °C along with increased urban development (Government of the Republic of Trinidad and Tobago 2020). In 2020, Trinidad and Tobago imported a value of USD 21.5M in air conditioners alone, accounting for 0.45% of total imports (Observatory of Economic Complexity 2020). Furthermore, the country imported a value of USD 19.1M in refrigerators, amounting to a further 0.4% of total imports (Observatory of Economic Complexity 2020).

Apart from space cooling, many industrial processes require systems to be cooled via a coolant. In many cases, the most common coolant used is water due to high heat capacity and low cost (Benedict et al. 2020). Water used for cooling typically enters the industrial system from water storage tanks or manmade ponds located within the facility. If the ambient temperature is higher due to extreme heat, the cooling capacity of the water decreases as it enters the system at a higher temperature than usual (Buryn et al. 2021). This subsequently reduces the efficiency of the process itself and can ultimately result in increased prices of the final product. In Trinidad, the industrial estates of Point Lisas, Frederick Settlement, Otahiete, La Brea, Point Fortin, and Galeota can be affected by this as these industrial plants are listed to use water as a raw material for cooling purposes (Water and Sewerage Authority 2014).

4.3. Social Responses: Heat Resilience Strategies

Trinidad and Tobago is classified as medium for extreme heat hazard, which means that there is more than a 25% chance that at least one period of prolonged exposure to extreme heat, resulting in heat stress, will occur in the next five years (ThinkHazard 2020). Out of the eleven regions in the country, only three (Tunapuna/Piarco, San Juan/Laventille, and Diego Martin) fall within the category of low (less than 1% chance); the others remain consistent with medium. Within these regions, those with pre-existing medical conditions such as respiratory-related illnesses, the elderly, children, persons who are uninsured, and persons employed outdoors are especially affected (Di Napoli et al. 2022).

In order to address the problems faced by citizens due to heat, the Government Republic of Trinidad and Tobago (GORTT) created the National Cooling Strategy of Trinidad and Tobago. The 2020–2030 policy sets out national initiatives to address sustainable and environmentally friendly refrigeration and cooling, aligning with the Montreal Protocol and Kigali Amendment. Furthermore, in partnership with the United Nations Development Program (UNDP) and the GORTT, ‘The Energy Efficiency through the Development of Low-carbon RAC Technologies’ project was created and funded by the Global Environment Facility (GEF). This project seeks to meet the nation’s cooling needs in an energy-efficient manner and will deliver multiple benefits at the local, regional, and global levels (Simon and Constance-Huggins 2022). Other energy-efficient strategies to reduce carbon emissions include an Electric Mobility (e-mobility) Policy for Trinidad and Tobago, which is at an advanced stage of development according to Mr. Kishan Kumarsingh, Head of the Multilateral Environmental Agreements Unit of the Planning and Development Ministry (Government of the Republic of Trinidad and Tobago 2021).

In addition to human health, livelihoods are also affected by extreme heat. Extreme heat has major repercussions for the agricultural sector (Khosla 2022). The National Food Production Action Plan 2012–2015, called "Agriculture Now," aimed to increase commodities grouped into staples, vegetables, fruits, aquaculture, livestock, and pulses and named cocoa and honey as their strategic crops (Shik et al. 2019). The cocoa crop is listed being as more resilient to climatic changes and would have greater potential than other crops (Eitzinger et al. 2015). However, greater investment is required to maintain innovations that will ensure stable and increased crop productivity in the changing climate (Lynch 2016).

Drought is a heat-related climatic variability and one which would be increased in frequency and intensity. To improve and manage the water resources of the country, the GORTT established the 'National Integrated Water Resources Management Policy'. It includes an objective to "minimize, mitigate and manage the impacts of flood, drought, and other water-related emergencies". On a household level, citizens utilize tanks during scheduled outages and cope with water stress (Fraser 2021). During drought conditions, grasses and trees dry out, becoming fuel for fires, and this can increase the probability of ignition and the rate at which fire spreads (NIDIS 2018). Therefore, the Ministry of the Environment launched the Forest Fire Prevention Programme in 2014 so members of the public can report the incidence of a fire (GORTT 2014).

There are other mitigation measures that benefit ecosystem health and help reduce temperatures, such as reforestation and tree planting. In 2005, the National Gas Company (NGC) replanted hectares of trees lost due to pipeline construction, and in 2018, they conducted a carbon sequestration study with the University of the West Indies (UWI) Office of Research Development and Knowledge Transfer. They found that the trees had sequestered 2243 tons of carbon, and the research team estimated that the numbers would reach 5228 tons by 2030. This accounts for at least 1% of the CO_2 tonnage the country aims to cut from the transportation sector by that date (Belle 2020). Furthermore, Adopt A River, which is an initiative developed by WASA, regularly plans and executes tree planting exercises and reforestation activities (Adopt a River 2021).

In more urbanized parts of the country, green roofing systems not only provide the owners of buildings with a proven return on investment but also moderate the heat island effect. Green roof temperatures can be up to 4 °C lower than those of convectional rooftops and reduce building energy use by 0.7% compared to conventional roofs, reducing peak electricity demand and leading to annual savings (EPA 2022). Another mitigation strategy which has not been utilized in the country but would be beneficial to heat reduction are cool pavements. These are composed of paving materials that reflect more solar energy and enhance water evaporation. Researchers predicted that an increase in pavement reflectance from 10 to 35% could potentially reduce city temperatures by (0.6 °C) which would lower energy use and reduce ozone levels (EPA 2012).

5. Conclusions

The information gathered in this study provides not only insight into the historical, current, and future changes in temperature and heat in Trinidad, but also the areas and regions most at risk. This study has highlighted a few key facts that require serious consideration. These are as follows:

- Trinidad has become significantly warmer with an increase in the maximum heat index over the past few decades, with temperatures expected to continue increasing.
- Urban areas in Trinidad have already developed into surface urban heat islands (SUHIs) and can potentially develop into full-fledged urban heat islands (UHIs) if there are continuous increases in unregulated urban development in Trinidad, as seen over the past few decades.
- The western and southwestern portions of Trinidad are most at risk (in all emission scenarios) regarding heat accumulation and heat-related impacts.

Looking forward, urban planning and design in Trinidad needs to be modified and adjusted in order to reduce expected heat-related climatic impacts within the most populated regions of Trinidad, which also coincide with the regions projected to be most impacted by heat. It is important that already-existing green spaces within these highly urbanized regions, such as Port of Spain and Diego Martin, are not removed, as this would exacerbate increases in temperatures and heat-related health risks to the people that work and reside in those areas. These green spaces serve to increase shadow effects and evaporative cooling, thus reducing heat accumulation. It is also important that the adaptive capacity and resilience be strengthened within these regions.

Unregulated urban development within vulnerable regions of west and southwest Trinidad should be carefully and thoughtfully rendered or ceased altogether in order to prevent large portions of the population of Trinidad being situated in regions where they would be prone to health risks due to heat-related impacts. At present, Trinidad is at a point where positive change can be enacted at an early stage to reduce future impacts on the multiple facets of life and various sectors already affected by increased heat.

This study provides detailed knowledge and insight into urban vulnerability to heat-related climate risks. This can allow for other scientists, policymakers, planners, and governing bodies to have a more comprehensive understanding of the urban thermal environment within small island developing states (SIDS). It also highlights the conditions that can aid in adaptation and mitigation, creating greater awareness and thereby informing the planning process regarding heat-related impacts within Trinidad and Tobago and the Caribbean region.

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