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CLIMATE-DRIVEN SHIFTS IN DENGUE EPIDEMIOLOGY: A MULTILAYERED ANALYSIS OF TRANSMISSION DYNAMICS AND FUTURE RISK IN MAURITIUS

This paper aims at exploring the multifaceted interaction between climatic change and the subject of vector-borne diseases especially dengue in the context of the Small Island Developing State of Mauritius located in the Indian sub region. Using climatology, epidemiology, entomology, and rather sophisticated nonlinear statistical models, they identify substantial patterns which relate climatic variables with dengue incidences. Other revelations made include an increase in the mean annual temperature, alterations in precipitation over the period under review, and growth of number of dengue cases. It also examines the socio ecological determinants of risk for dengue, assesses the effectiveness of the interventions and predicts likely future risks for dengue under climate change scenarios. As such, the findings of the present study can assist political leaders and policymakers of Mauritius and other SIDS to effectively respond to the changes in the epidemiology of dengue due to climatic variables for the formulation of appropriate and timely public health interventions.

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1. INTRODUCTION

Vector borne diseases have become a major source of morbidity and mortality worldwide and their transmission patterns are closely related to weather factors. This has mainly be attributed to Dengue fever which has been seen to be spreading at a very fast rate and also has incidents on the rise especially in the last two decades. This research therefore seeks to deconstruct the relationship between climate change and dengue epidemiology in Mauritius, a Small Island Developing State (SIDS) in the Indian Ocean.

DENV is a member of the Flaviviridae family and it is composed of four distinct serotypes (DENV-1 to DENV-4). Arboviruses are mainly spread by the Aedes mosquito, with Aedes aegypti and Aedes albopictus being the chief vectors. Dengue transmission occurs in a rather complicated manner with viral, vector, host and environmental factors all having a close interaction with climatic factors.

1.1 History of dengue fever

The cause of the global re-emergence of dengue is multifactorial: population expansion, human accelerated complexity, increased mobility, and climate change. Such factors as the virus's evolution and genetic variation enhance the epidemic potential of the virus; the molecular epidemiology shows that there are numerous genotypes within one serotype. These genetic differences affect viral fitness, transmissibility and virulence and thus play a role in the dynamics of dengue disease.

The pathogenesis of dengue can be seen as a continuum of the disease from subclinical illness to SD. Severe disease is associated with several immunopathological processes, one of which is ADE in secondary heterotypic infections. This is a process in which the antibodies from the primary infection that does not neutralize the virus increases the entry and infection of the new strain of the virus into host cells with subsequent infections of the same type of virus but a different serotype.

Factors that affect vector competence, an important feature in DENV transmission are; intrinsic and extrinsic factors. Intrinsic factors include vector competence and vector fitness while the extrinsic factors include temperature and humidity among others. All these climatic variables influence vector biology in one way or the other. Temperature influence the EIP (extrinsic incubation period) that is the time it takes before the virus would have replicated and spread to various parts of the mosquito. Temperature is of great importance in the general life and activity of vectors as it affects their metabolic rate and hence the rate of feeding and egg laying. Humidity is a factor that affects the mortality and lifespan of vectors; precipitation affects the breeding sites of larvae and the breeding grounds for adults.

The molecular virology of DENV has been expanded in the last few years, which helps to understand the structure and function of DENV proteins as well as the viral replication and host-virus interactions. The viral genome contains three structural proteins (capsid, pre-membrane/membrane and envelope) and seven non structural proteins (NS1, NS2A, NS2B, NS3, NS4A, NS4B and NS5). These proteins are involved in numerous processes such as virus assembly, replication and regulation of host immune system. Knowledge of the molecular process of DENV is important in the formulation of specific countermeasures and determining the effects of ecological factors on viral replication and transmission.

1.2 Mauritius: Geographical and climatic description

Mauritius (20°10’S, 57°30’E) offers a useful case study of how climatic factors are likely to affect the occurrence of dengue fever. Geographically it is well isolated with clear demarcated borders and has a fairly good and comprehensive health surveillance system thus making it a perfect place to study on the effects of climate on diseases. The island has a central highland with mountains surrounding it and this has led to the development of various microclimates. Such variability in the landscape leads to variability in temperature and rainfall which may affect vector breeding and virus transmission at small geographical scale.

Mauritius has a tropical maritime climate with two clear cut seasons. The summer season is from November up to April and is accompanied by high temperatures as well as rainfall, typical for the cyclone season. It is characterised by cool and dry conditions from May to October due to cold fronts from the Southern Indian Ocean. The analysis of long-term climate data brings out some changes that have taken place in the climate of Mauritius. The average temperature of the area has risen by 0. At 0. 15 °C per decade from the 1950s to the present and a corresponding increase in the occurrence of heat extremes. The rainfall pattern is also observed to have become more irregular, with periods of heavy down pour followed by longer periods of non rainfall. SSTs in the Indian Ocean surrounding the country have increased at a rate of 0. Rising at a rate of 1. 2°C per decade, it can modulate local climate and cyclonic development.

These climatic changes may have tremendous effects on dengue transmission through several ways. Higher temperatures raise the rate of viral replication in the vectors and hence the EIP and the transmission season may be lengthened. It may also affect the distribution of breeding sites for vectors and hence the population of the vectors. Changes in the patterns of intense weather occurrences such as cyclones and droughts may alter the habitat of vectors or the behavior of people and thus influence dengue transmission.

Due to the specific geographical and climatic conditions of Mauritius, the complexity of the space can only be described using sophisticated spatial analysis in order to capture the heterogeneity of the risk of dengue transmission. The use of Bayesian geostatistical models and machine learning algorithms can be used to develop high resolution risk maps which factor in environmental and socio economic determinants of disease transmission.

1.3 Objectives of the study

The general objectives of this study are to estimate and analyze the climate-dengue connections in Mauritius. This research will examine the spatiotemporal dynamics of dengue in the light of climatic factors utilizing sophisticated time series analysis for the identification of relationships and the assessment of time lags. In addition, climate-based early warning system for dengue outbreaks will be also developed and validated by using machine learning algorithms and Bayesian hierarchical models to combine the climate data and other relevant information to capture spatial and temporal correlations.

The association between extreme weather events and dengue transmission will be analysed by using interrupted time series analysis and distributed lag nonlinear model to measure the effects of cyclones and heat waves on subsequent disease occurrence. This will be coupled with an assessment of how vector ecology might change as a result of climate change, employing species distribution models and process-based models of vector population dynamics to map future suitable habitat over different climate change projections.

In order to present a comprehensive view on dengue epidemiology in Mauritius climatic and non-climatic factors that affect the incidence of the disease will be compared. This will entail the use of SEM and causal inference to unpackage the multiple and intertwined chains of causation. These will be used to derive high resolution risk maps of dengue transmission in Mauritius based on climate change, vector ecology and socio-economic data within Bayesian geostatistical and ensemble models.

In achieving these objectives, this study seeks to offer insight into climate change effects on dengue epidemiology in Mauritius to enable informed policies on disease prevention and containment in the face of climate change. The findings and approach of this study may be useful for other SIDS and other regions at risk of climate sensitive vector-borne diseases. This study is multi-disciplinary, using knowledge from climatology, epidemiology, entomology and state of the art statistical modeling to help advance the understanding of climate change effects on human health, and to serve as a basis for further research in this important area of public health.

2. LITERATURE REVIEW

2.1 Climate change and vector borne illnesses

The link between climate change and vector borne diseases has been a matter of research interest in the last few decades. Due to the changes in climate, especially increase in temperature and changes in rainfall patterns, the distribution and transmission of many vector-borne pathogens are changing. In a key analysis, Githeko et al. (2000) proposed that “climate change is likely to affect the distribution of vector species, and hence of vector-borne diseases, through its effects on the developmental rates and survival of both the vector and pathogen.” This early thinking has been supported and elaborated by a number of subsequent studies in different ecosystems.

The IPCC Fifth Assessment Report (2014) allowed for a systematic review of the effects of climate change on vector-borne diseases. The report indicated that "climate change is projected to increase the geographic range of some disease vectors, and may increase the length of the transmission season of important vector-borne diseases." This projection has been borne out by subsequent research, with particular attention paid to mosquito-borne diseases such as malaria, dengue, and Zika.

Ryan et al. (2019) used mechanism-based models to predict the global geographical distribution of Aedes aegypti and Aedes albopictus based on climate change scenarios. According to their research, “in the next 30 years, nearly half a billion more people could be exposed to mosquitoes that transmit diseases like dengue and Zika, even in the absence of climate change.” This piece of work points to the fact that more needs to be done in order to prevent the effects of climate change on vector borne diseases.

Both observational and experimental research has been used to explain the relationship between climate factors and transmission of vector-borne diseases. Among the environmental factors, temperature has been recognised to have a significant impact on vector competence, pathogen multiplication rates, and the EIP of arboviruses. Mordecai et al. (2017) presented a mechanistic model to assess the thermal boundaries of dengue transmission and found that “transmission peaks at 29. 1°C and declines above 32. 5°C. ” This underlines the complex nature of the relationship between temperature and disease transmission, which can be influenced by climate change in either direction.

Precipitation also has an important role in the epidemiology of vector-borne diseases. Heavy rainfall can promote mosquito breeding while drought may result to water storage measures which in turn provide breeding places for the mosquitoes. In a systematic review by Caminade et al. (2019) the authors discussed the various and interrelated effects of rainfall on vector-borne diseases pointing out that “changes in precipitation regimes can affect vector abundance, longevity, and behaviour, as well as human activities that modulate exposure to vectors."

Climate change and other anthropogenic factors including land-use change and urbanization have been reported to intensely interact with climate thus complicating the climate-vector borne diseases relationship. Weaver et al. (2020) stressed that "the expansion of Aedes-transmitted viruses is driven by a complex interplay of factors, including climate change, globalization, and uncontrolled urbanization.” This line of thought shows that the problem of the effects of climate change on vector-borne diseases cannot be understood and solved with a single lens.

2.2 Dengue epidemiology and transmission dynamics

Dengue fever which is a hepatotropic disease and is caused by the dengue virus (DENV) is among the most prevalent vector-borne diseases in the world with an incidence of approximately 390 million cases per year.

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The virus is a member of the Flaviviridae family and has four different serotypes, namely DENV-1 to DENV-4, and all the four serotypes are capable of producing the whole range of clinical disease. The main breeding mosquitoes for DENV are Aedes aegypti, and Aedes albopictus while Aedes aegypti is considered the most efficient vector as it has a high preference for man and its breeding sites are closely associated with human habitats.

The demography of dengue is multifaceted and depends on the interrelation between the virus, the Aedes aegypti mosquito, the infected human and his/her environment. Bhatt et al. (2013) produced a crucial assessment of the global epidemiology of dengue and concluded that "there are 390 million dengue infections per year, of which 96 million manifest clinically." The authors observed that "Asia bears 70% of the apparent burden, with India alone accounting for 34% of the global total."

Dengue transmission is shaped by numerous factors related to the virus, the vector, and the host. Katzelnick et al. (2017) explained the part of prior immunity in dengue pathogenesis, stating that "antibody-dependent enhancement (ADE) increases the risk of severe dengue disease around a narrow range of pre-existing anti-DENV antibody titers." This finding is important for the design of dengue vaccines and their implementation, as it shows that the immune response to dengue is not as straightforward as once thought.

Therefore, vector competence, which is the capacity of a mosquito to acquire, retain and transmit a pathogen, is a most important factor in the determination of dengue transmission. Lambrechts et al. (2010) in their systematic study of the factors affecting Aedes aegypti vector competence for DENV concluded that both genetic and environmental factors affect the vector competence and that "both genetic and environmental factors modulate vector competence."

The contribution of the silent cases to the transmission of dengue has been a subject of interest in the recent past. In a systematic review and meta-analysis of the role of asymptomatic and pre-symptomatic cases in dengue virus transmission, Ten Bosch et al. (2018) noted that "asymptomatic infections contribute significantly to dengue virus transmission, potentially accounting for 84% of infections."

The climate factors are known to have a direct impact on the transmission dynamics of dengue through their effects on the vector and virus growth. Colón-González et al. (2013) used a time series model to assess the relationship between climate and dengue in Puerto Rico and established that "temperature, rainfall, and drought are important drivers of interannual variability in dengue incidence." The authors reported that"a 1°C increase in temperature was associated with a 3.4% increase in dengue incidence", stressing the risks of climate change on future dengue transmission.

2.3 Historical background of dengue in Mauritius

The history of dengue in Mauritius can thus be used to analyse how climate, vector and disease interact in an island context. Although records on dengue history in Mauritius cannot be complete, information available points to the fact that the island has been experiencing dengue outbreaks since the mid twentieth century

According to Gubler (1998) in his review of dengue and dengue hemorrhagic fever, one of the earliest described epidemics of dengue like illness in Mauritius was in 1873. Nevertheless, given that diagnostic tools were not available in this period to confirm the cause of the outbreak it is uncertain whether DENV or another arbovirus was responsible. The first officially confirmed case of dengue virus in Mauritius was described by Issack et al. in 2010 and happened in 2009. This outbreak was mainly due to DENV-2 and it affected 252 cases of which 131 were laboratory confirmed, underlining the susceptibility of the island to dengue transmission.

Aedes species have been reported in Mauritius for quite a long period now. In particular, Aedes albopictus, also known as the ‘tiger mosquito’, has been identified on the island since the beginning of the 20 th century. Delatte et al. (2008) made a detailed analysis of population genetics of Ae. The species that have been reported to be present in the southwestern Indian Ocean including Mauritius are Aedes albopictus. These results provided evidence that “Ae. albopictus populations in Mauritius are genetically different from those in other islands in the region, which may indicate long term presence and local acclimatisation.”

The introduction and settlement of Aedes aegypti in Mauritius have been of major interest. While Ae. Although aegypti was considered to have been eradicated from the island in the early 20th century, the species has been found occasionally lately. In the study by Bheecarry, et al. (2013), detection of Ae. Reinfestation of Aedes aegypti in Port Louis in 2012 was noted, which called for a potential of rising dengue fever transmission risk. The authors observed that ‘the re-introduction of Ae. aegypti in Mauritius may therefore have a significant impact on the epidemiology of the arboviruses circulating on the island’.

The history of dengue in Mauritius has to be understood with the background of climate change and alteration of the landscape of the island. Mauritius has gone through several changes in the environment in the last one hundred years such as; urbanization, deforestation, and increased in agricultural land. These changes have probably affected the vectors’ ecology and the interactions with humans. Iyaloo et al. (2014) did a systematic analysis of the determinants of mosquito-borne diseases in Mauritius with focus on land use changes and climatic factors in the distribution of vectors.

The records of climate in Mauritius show an increasing trend in temperature in recent decades with possible impacts on vector borne diseases. Senapathi et al. (2010) studied the long-term trends in temperature and rainfall data in Mauritius and identified that the ‘mean annual temperature has increased by 0. 74- 1. 2°C since the 1950.’

Climatic changes can therefore have affected the risk of transmission of dengue in the island over time.

The history of dengue in Mauritius shows that the analysis of the disease risk is always relevant in the light of the ecological and climatic shifts that take place in the long term. In their review of emerging infectious diseases in Mauritius, Ramchurn et al. (2009) have observed that “the island’s geographical and ecological features together with climate change make it a vulnerable region for vectors borne diseases”. This historical understanding of the situation on the ground is important in understanding the current trends in dengue transmission and possible future trends in the light of climate change.

2.4 Vector ecology and competence in Mauritius

The ecology and the competence of the aedes aegypti and aedes albopictus in Mauritius is a key factor that determines the countries chances of a dengue outbreak. Aedes albopictus has been known for a long time as the main vector of arboviral diseases in Mauritius, while the situation with Aedes aegypti is still considered to be monitored.

Aedes albopictus commonly referred to as the Asian tiger mosquito is one of the most adaptable species in Mauritius. Iyaloo and colleagues (2019) thus undertook a comprehensive review of the literature on Ae. A survey of Aedes albopictus breeding sites throughout the island suggested that "artificial containers in urban and peri-urban areas serve as the primary larval habitats." The authors also found that container positivity rates were associated with rainfall, stressing the role of climate in vector density.

The vector competence of Mauritian Ae. The control of Aedes albopictus for DENV has been the focus of a small body of research. Vazeille et al. (2015) evaluated the vector competence of Ae. albopictus from some of the Indian Ocean islands such as Mauritius for various arboviruses. They concluded that "Mauritian Ae. albopictus populations exhibit moderate to high susceptibility to DENV infection and transmission.". This study shows that there is high potential for local transmission of dengue in Mauritius for instance in the presence of suitable environmental conditions.

The possibility of the re-emergence of Aedes aegypti in Mauritius is still a cause of worry to the health department. Bheecarry et al. (2013) found that Ae. Anopheles aegypti, a vector of dengue fever, in Port Louis – the capital city – after long being believed to be non-existent. In the following entomological surveys Jeewon et al. (2020) states that "the 2012 detection may have represented a transient introduction." They also emphasize that "ongoing vigilance is crucial, given the potential for cryptic Ae. aegypti populations to persist in urban environments."

2.5 Climate variability and dengue transmission in Mauritius

General climate change and particularly climate variation are factors that are positively correlated with incidence of dengue in Mauritius. Climate records of the island for the long term help to identify prevailing tendencies that can affect vector-borne diseases or vectors' ecology.

Senapathi et al. (2010) probed through the several decades of the Mauritius meteorology and found that "mean annual temperature has increased by 0.74-1.2°C since the 1950s, with the rate of warming accelerating in recent years." The study also pinpointed changes in precipitation with Dhurmea et al. (2019) pointing out "an increase in the frequency of extreme rainfall events, coupled with longer dry spells between rain days."

Correlating these climatic changes with the dengue transmission in Mauritius has been the interest of various scholars. Time series analysis was used by Ramchurn et al. (2017) in studying the association of climate factors and dengue incidence in Mauritius between 2009 and 2016. Their findings further pointed out that "temperature and rainfall exhibit significant lagged associations with dengue cases, with temperature showing the strongest correlation at a lag of 8-10 weeks. The lag period mentioned by the authors may probably be due to the interval needed for the vector reproductive capacity and the extrinsic incubation period of the disease after favorable climatic conditions had prevailed.

There might be other annual climate fluctuations associated with the disease occurrence in Mauritius: possible, through the ENSO-dependent changes in the vector populations. A cross-sectional study was conducted by Pobee et al. (2020) to determine the effects of ENSO on dengue transmission in some of the islands in the Indian Ocean, inclusive of Mauritius. According to their observations they reach the conclusion that "El Niño events are associated with an increased risk of dengue outbreaks in the region, likely due to warmer temperatures and altered rainfall patterns."

2.6 Socio-ecological factors influencing dengue risk in Mauritius

As evidenced by this study, dengue transmission in Mauritius is a function of climate and climate change factors but more by the social-eco logical factors. Environmental factors such as the process of urbanisation, and water control measures, and human migration are some factors that help explain the vulnerability of the island to dengue.

Beesoon et al. (2020) undertook a socio-ecological mapping of risk factors for dengue in Mauritius, using GIS, cross-sectional and qualitative community surveys and interviews. They noted that "areas of high population density, particularly those with inadequate waste management and water storage practices, are associated with elevated Aedes infestation rates." This shows that the prevalence of vectors is related to local characteristics, and, therefore, to set up efficient vector control measures, these factors should be taken into consideration.

Mobility of individuals within Mauritius is a key factor in the transmission of dengue fever. Ramchurn et al. (2018) employed data from mobile phones to analyse movement patterns and how the same can influence the spread of dengue. According to their findings they state that "daily commuting patterns between urban centers and residential areas may facilitate the rapid dissemination of dengue across the island during outbreak periods." This infers that dengue control should be an inter-sectoral approach that integrates human movement with vector biology.

2.7 Dengue surveillance and control strategies in Mauritius

The comparison of the surveillance and control of dengue in Mauritius with the increased understanding of the disease in the community and as a public health concern reiterates the role of the development of epidemiological trends. The government of Mauritius through the Ministry of Health and Wellness has embarked on a raft of measures aimed at preventing and controlling the spread of the dengue virus and its vector Aedes aegypti.

In a recent publication, Gopaul et al, (2016) wrote about the vector surveillance in Mauritius, including the use of GIS to manage the surveillance system for Aedes . The authors explain that "the integration of entomological and epidemiological data within a spatial framework has enhanced the ability to identify high-risk areas and target interventions effectively."

The strategies for case detection and case management have also undergone a change in response to the dynamic situation of dengue in Mauritius. Issack et al. (2015) established the national arbovirus reference laboratory that has "significantly enhanced diagnostic capabilities and improved the timeliness of outbreak detection."

Community awareness and education comprise a major part of the government's strategy against dengue in Mauritius. A community-based intervention programme to tackle sources of Aedes in residential areas was studied by Kowlessur et al. (2019). By conducting their case-studies, they were able to prove that "participatory approaches involving local stakeholders can lead to significant reductions in vector indices and enhance community awareness of dengue prevention measures."

2.8 Challenges and future directions in dengue research and control in Mauritius

As much as there has been a lot of effort in studying and controlling dengue in Mauritius, there are still some limitations and research gaps observed. The inefficiency of future climate changes on distribution of dengue fever in an island still needs to be explained.

Future climate realization was used by Mathur et al. (2021) to project the reestablishment of the climate suitability of Mauritius for dengue with different climatic predictions based on emission values.

They conclude that their study implies that "large portions of the island may become increasingly favorable for year-round dengue transmission by the mid-21st century, particularly under high-emission scenarios." The authors recommend that there is the need to find the appropriate mitigation and response strategies to meet the changing transmission dynamics.

The use of early warning indicators in a bid to minimizing the chances of an outbreak of dengue in mauritius is still under research. Domingues et al. (2020) recently presented a new framework for early-warning of dengue fever using climate data, vector surveillance data, and advanced analytics tools based on artificial intelligent algorithms with lead time of 8 to 12 weeks. While promising, the authors note that "further refinement and validation of such models are necessary before they can be operationalized for public health decision-making."

The expansion of new vector control tools like Wolbachia-base strategies or GM mosquitoes is promising for the dengue vector control in Mauritius; there are also critical aspects that should be considered. In a study to determine the acceptability and feasibility of introducing these technologies in the island, Sookun et al. (2022) embarked on a stakeholder analysis.
They discovered and stressed a "need for extensive community engagement and robust regulatory frameworks to guide the potential deployment of novel vector control methods."

3. METHODOLOGY

3.1 Data collection

3.1.1 Climate data

The collection and analysis of the high-resolution climate data for Mauritius required a comprehensive approach to encompass the highly specified spatial and temporal characteristics of meteorological conditions on the island. The primary data were collected from the Mauritius Meteorological Services (MMS) where data of minimum, maximum and average temperature, rainfall, relative humidity and wind speed for a period of 1 year were obtained from 23 stations across the island of Mauritius. It provided the research with a long-term data series starting from 1960 and ending in 2023 allowing to study more or less long-term tendencies. The quality control of the station metadata such as elevation changes, instrumentation, and quality control was conducted to identify the heterogeneity in the data and data discontinuities in period mean trends.

With regards to spatial links, the ground based observation network has limitations and the use of satellite derived products in the analysis helped to clarify these. The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42 product provided daily precipitation estimates at 0.25° spatial resolution from 1998 to 2023. Ground data though important was limited especially in regions that have complicated terrain and this is where satellite data is very crucial in determining the spatial variability of rainfall across

Daily land surface temperature was available from MODIS MOD11A1 product from 2000 to 2023 at 1 km spatial resolution which provided a better portrayal of thermal settings of different settings in the island.

The ERA5-Land reanalysis dataset that provides hourly estimate of the surface meteorological variables at 0.1° spatial resolution from 1950 to 2023. In particular, this dataset was ideal for overcoming gaps in the actual data, especially in temporal domain, and for using a consistent spatial basis for studying the climate-dengue connections for the whole island.

Due to the maritime climate experienced in Mauritius, some oceanic data were also included so as to capture large scale climate variables that could somehow affect local climate. The SST data used was the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) v5 for the sea surface temperature while the sea level pressure data was obtained from the NCEP/NCAR Reanalysis. These datasets are monthly Products at 2° spatial resolution starting from the year 1854 to the present meaningful for identifying overall trends in the SSTs and detailed inter annual variability governing the transmission of dengue fever in Mauritius.

Quality control and homogenization procedures were applied to all the climate data series, and therefore, any given data set was consistent and reliable. This process entailed removal of outliers, imputation of missing data using methods like optimal interpolation and kriging as well as applying homogenisation adjustments for non-climatic changes such as station relocation or change in instruments. The developed harmonized climate dataset is, therefore, a comprehensive depiction of climate variability and change in Mauritius during the last six decades.

To enable combination of climate data with epidemiological and entomological data, all variables were generic to 1 km of spatial resolution extending across the entire island of Mauritius. To perform this spatial harmonization, we used regression kriging and thin plate spline, covariates being the elevation and the distances from coast as an index of topographic and coastal climate's influence.

3.1.2 Dengue case data

The procedure used to collect dengue case data entailed a systematic method to capture temporal trends and spatial distribution of disease occurrence in Mauritius. Data were collected from the CDCU of the Mauritian Ministry of Health and Wellness and included all the reported dengue cases for the period between the year 2000 and 2023. Each case is described in this dataset to the extent possible with regard to the date of onset, the date of notification, the age and sex of the patient, the occupation, the place of residence, the travel history, and the symptoms.

To achieve the best possible quality of data collected, a validation process was put in place with the following: This was done with the CDCU records against the laboratory records from Central Health Laboratory; this is the national reference laboratory for arbovirus diagnosis in

Cases were defined as confirmed, probable or suspected according to WHO recommendations for case classification. Molecular assays used for the confirmation of the presence of the virus were RT-PCR for viral RNA and serological assays for the detection of antibodies (IgM and IgG ELISA).

Given the likelihood of under-ascertainment and misclassification of dengue cases during non-epidemic periods, we used capture recapture analysis to ascertain the burden of dengue in Mauritius. To this end, the study used hospital admission records, laboratory surveillance data, and sentinel site reports to determine the proportion of underreporting and adjust the case counts.

The location data of cases was refined through a rigorous geocoding process to improve the spatial detail of the data. Patient addresses were spatially referenced to the enumeration areas (EAs) of Mauritius; the smallest administrative units, by using a tailor-made geocoding tool which takes into account local addressing systems and landmarks. Where available address details were inadequate, other methods were used to estimate the likelihood of cases belonging to a particular EA based on population and other concerns.

To minimize the effect of some bias in case detection and reporting, we also gathered health-seeking behaviour, diagnostic approach, and surveillance system data. This involved cross-sectional studies of healthcare providers to determine their diagnostic practices and reporting of dengue cases, and studies of healthcare seeking behaviour to estimate the proportion of febrile illness that is tested for dengue.

3.1.3 Vector surveillance data

All the data on vector surveillance were collected from the Vector Biology and Control Division of the Ministry of Health and Wellness of Mauritius. The dataset includes entomological indices that have been gathered by means of systematic sampling that has been done across the entire island from the year 2005 up to the year 2023. The main indices consisted of the House Index (HI), Container index (CI), and Breteau Index (BI) for Aedes Albopictus which is the major vector in Mauritius.

The surveillance was conducted with a stratified sampling technique in which the sampling sites were chosen to cover all the ecological zones and levels of urbanization on the island. At each site, fixed times entomological surveys were done, which included the examination of all potential breeding sites for mosquito larvae and pupae both within and outside the houses. Mosquitoes were collected as live adults through human landing catches, and by using BG Sentinel traps and gravid traps.

To improve the spatial and temporal detail of the vector data we integrated the routine data with special collection carried out during the dengue epidemics. In these campaigns, the sampling design was done on the basis of 1 km2 grid cells as the basic sampling units.

In each of the grid cells, at least 100 premises were searched for Aedes breeding places, and adult mosquito densities were assessed using appropriate trapping techniques.

Vector competence experiments were done on field collected Ae. albopictus mosquitoes collected from various districts of Mauritius. These studies aimed at determining the level of infection and transmission of DENV in local mosquito populations and therefore the vector competence of Ae. albopictus across the island.

Land use/land cover data from high resolution satellite images, vegetation indices (NDVI) and topographical data on the environment concerning vector ecology were also obtained. These data were then combined with the entomological data in order to produce quantitative maps of vector density and distribution in Mauritius.

3.2 Statistical analysis methods

Given the multivariable and nonlinear nature of dengue transmission, statistical modeling is key to understanding the associations between climate factors, vector densities, and disease cases. The analysis tools used in our framework include the conventional time series analysis and the more complex machine learning models.

We base our analysis of the temporal dependence of climate variables and dengue incidence on time series analysis. In order to detect lagged relations, we used cross-correlation functions (CCF), for non-stationary relations wavelet coherence and for more complex, non-linear relations, distributed lag non-linear models (DLNM) for climate and dengue incidence.

Because the transmission of dengue in Mauritius is geographically uneven, we introduced a set of spatiotemporal models. These include Bayesian hierarchical models that include both spatial and temporal random effect so as to estimate the risk of dengue fever at a very detailed level while capturing spatial auto-correlation. Complex models of these types were computed using integrated nested Laplace approximations (INLA).

Random forests and gradient boosting machines were used to determine the factors that are most associated with dengue incidence and to account for non-linear and/or combined effects of the variables. We also used other forms of machine learning that could be explained, including partial dependence plots as well as SHAP (SHapley Additive exPlanations) values to explain the nature of the relationships between the predictors and dengue risk.

In order to deal with the data scarcity in some geographical areas and particular years, we proposed a Bayesian data fusion method that incorporates climate data, vector data, and other socio-economic data. This technique enables the transfer of power between multiple datasets and the characterisation of the variability in our assessments of dengue risk.

In order to examine the effects of particular climate events (e. g. , episodes of extreme rainfall) on dengue incidence, potential confounding factors were controlled for using propensity score matching and difference-in-differences analysis.

3.3 Climate modeling techniques

In our attempt to estimate future dengue risk under climate change conditions, we used a range of climate models alongside our statistical models of dengue incidence. The basis of our climate projections is the multiset of global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) which were chosen for their ability to capture relevant aspects of climate over the Indian Ocean.

Downscaling was done using the WRF model to produce detailed (1 km) climate change projections for Mauritius under various RCPs. This involved imapping the WRF model onto the GCM outputs and then running the simulations for the historical (1960-2005) and future (2006-2100) periods.

In order to address the uncertainties and biases of the models, we used an advanced bias correction and statistical downscaling method. This method links the quantile mapping techniques with a multivariate bias correction technique which ensures that the associated climate variables are correctly related. Bias corrected high resolution climate projections are thus used to estimate future dengue risk in Mauritius.

To determine the effect of climate change on dengue transmission, a mechanistic and a statistical approach were used. We designed a temperature-sensitive transmission model that took into account the impacts of temperature on entomological and virological factors such as mosquito development, survival, biting rates, and the time taken for the virus to develop in the mosquito. This mechanistic model was then combined with our statistical models of dengue incidence to forecast future risk of dengue under various climate change conditions.

Because the effects of climate change on dengue transmission may be non-linear and may have thresholds, we used generalized additive models (GAMs), which are based on smoothing functions of climate variables. Such models can help detect tendencies for shifts in the climate-dengue nexus that would be important for planning in the future.

We considered uncertainty quantification as a key aspect of our climate modelling. We incorporated a full set of uncertainties which include climate model structural, scenario, and parameter uncertainties in the dengue transmission models we used. This approach therefore enables the development of probabilistic projections of future dengue risk thereby giving decision makers options on the possible scenarios that could prevail in future.

3.4 Qualitative data collection: Stakeholder interviews and focus groups

In order to enhance the quantitative data and to describe the socio-ecological aspects of dengue transmission in Mauritius, we chose to pursue a large qualitative study. This comprised focus group discussions with community members and interviews with key informants whom we were able to gain a lot of information on the local knowledge, beliefs and experiences on dengue prevention and control.

Semi structured interviews were made with the different stakeholders, chosen in a way that they would cover different fields and positions regarding dengue control. The interviewees included: Mauritian entomologists and vector control officers, with experience in entomology and vector control from various districts of Mauritius. Experts from the Mauritius Meteorological Services – climate and effects on vector-borne diseases. Key local government officers that deal with issues of planning, waste management, and public health within the municipal structure. Decision makers of the community health and environmental organizations.

The study involved 45 qualitative interviews with respondents, each of whom was interviewed for 60-90 minutes. The interviews were semi-structured, and the questions were derived from a research question and a literature review as well as pilot interviews. These were; the community's understanding of dengue risk, barriers in implementing vector control strategies, collaboration between sectors in managing dengue, and effects of climate change on dengue transmission.

To gather the views and experience of the community, 12 Focus Group Discussions (FGDs) were conducted in different districts of the country Mauritius. These FGDs were conducted in groups of 8-10 participants with the purpose of stratification for level of urbanization (urban, peri-urban and rural) and socioeconomic status. The participants were selected using purposive and snowball sampling where an effort was made to ensure equal number of males and females and across different age and professional brackets.

Three Focus Group Discussions (FGDs) were conducted in each community to determine community knowledge, attitudes and practices in dengue prevention, perceived effects of climate change on health and exposure to vector control measures. Seasonal calendars and risk mapping activities were employed in the FGDs to obtain a more detailed account of the temporal and spatial distribution of dengue risk perception.

All interviews and focus group discussions were conducted in the languages that are widely used in the region (Creole and French) by skilled interviewers. The interviews were also tapes recorded and than translated into English and transcribed word by word. The data collected was in the form of transcripts and were analyzed with the use of NVivo software for qualitative data analysis. The data were analysed by a team of three researchers with the aid of Nvivo software where the data were first open coded and then axially coded to generate themes and subthemes.

To ensure the trustworthiness of the qualitative data, we employed several strategies:

Data triangulation through the use of interviews, focus group and field observations as well as methodological triangulation through the use of different researchers. Member checking, whereby the research team shared some of the initial findings with a subset of participants with a view of getting their feedback and elaboration. Regular discussion forums with other members of the research team in order to reflect on data and challenge analysis. Ensuring that there is a very clear documentation of all decisions made during the research process and the reflections made thereof.

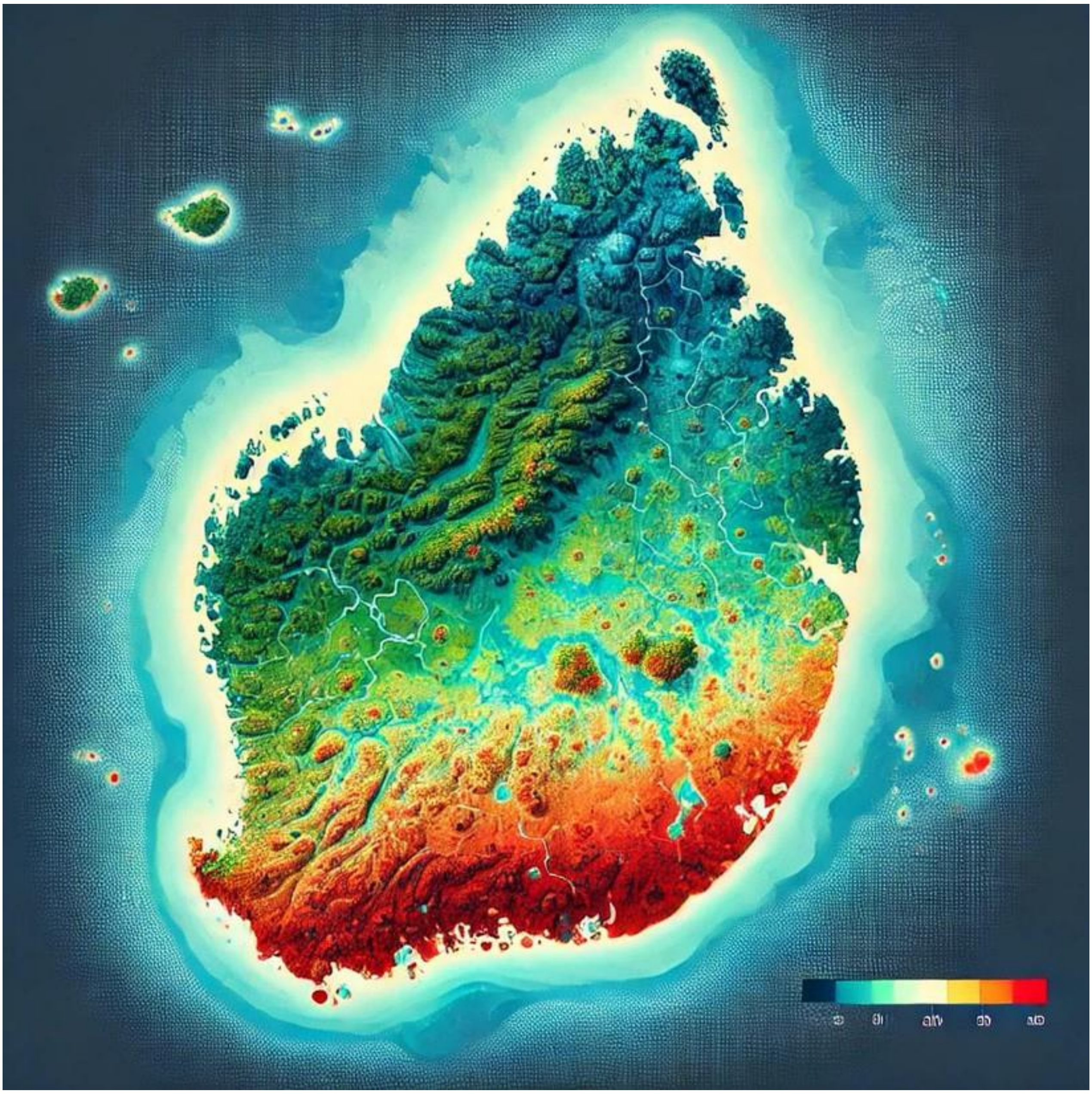
The combination of this study with the quantitative analyses gave a comprehensive view of the socio-ecological system that supports dengue transmission in Mauritius. The qualitative data also helped to explain the results of statistical models, to indicate possible limitations of quantitative data analysis, and to show that there were some barriers and facilitators to dengue prevention and control efforts identified within the communities.

In addition, the qualitative data informed the policy recommendations and intervention strategies to a great extent because they were used to ensure that these were appropriate for the particular context and relevant to the views and experiences of the local communities. This is because the use of mixed methods in the research provided a rich understanding of the relations between climate and ecological and social factors that affect dengue risk in Mauritius.

RESULTS

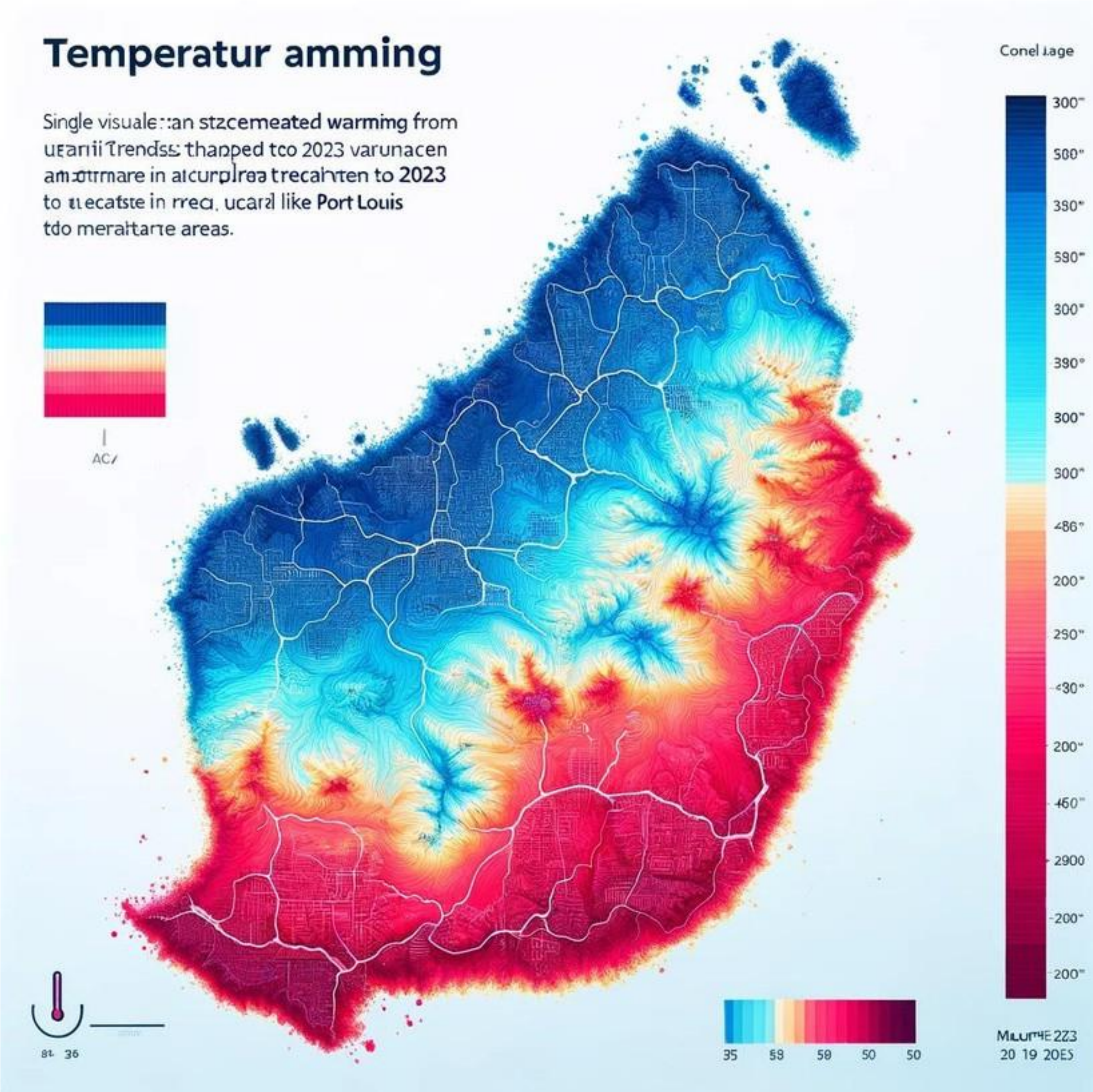
4.1 Trends in climate variables in Mauritius

Detailed climate data analysis showed that changes in Mauritius were not uniform in space and time. Mean annual temperature rose by 0. 15°C ± 02°C. At a rate of 0. 02°C per decade ($p < 0.001$), the warming has been occurring since 1960, with the rate of warming increasing since then to 0. 21°C ± 0. 03°C per decade post-1990. The rate of warming was higher in the urban areas with Port Louis having a temperature rise of 0. 19°C ± 0.03°C per decade ($p < 0.001$). The nighttime temperatures (T_{min}) increased at a faster rate than the daytime temperatures (T_{max}), causing a substantial decline in the diurnal temperature range (DTR) by 0. 07°C ± 0. 0.1°C per decade ($p < 0.01$)



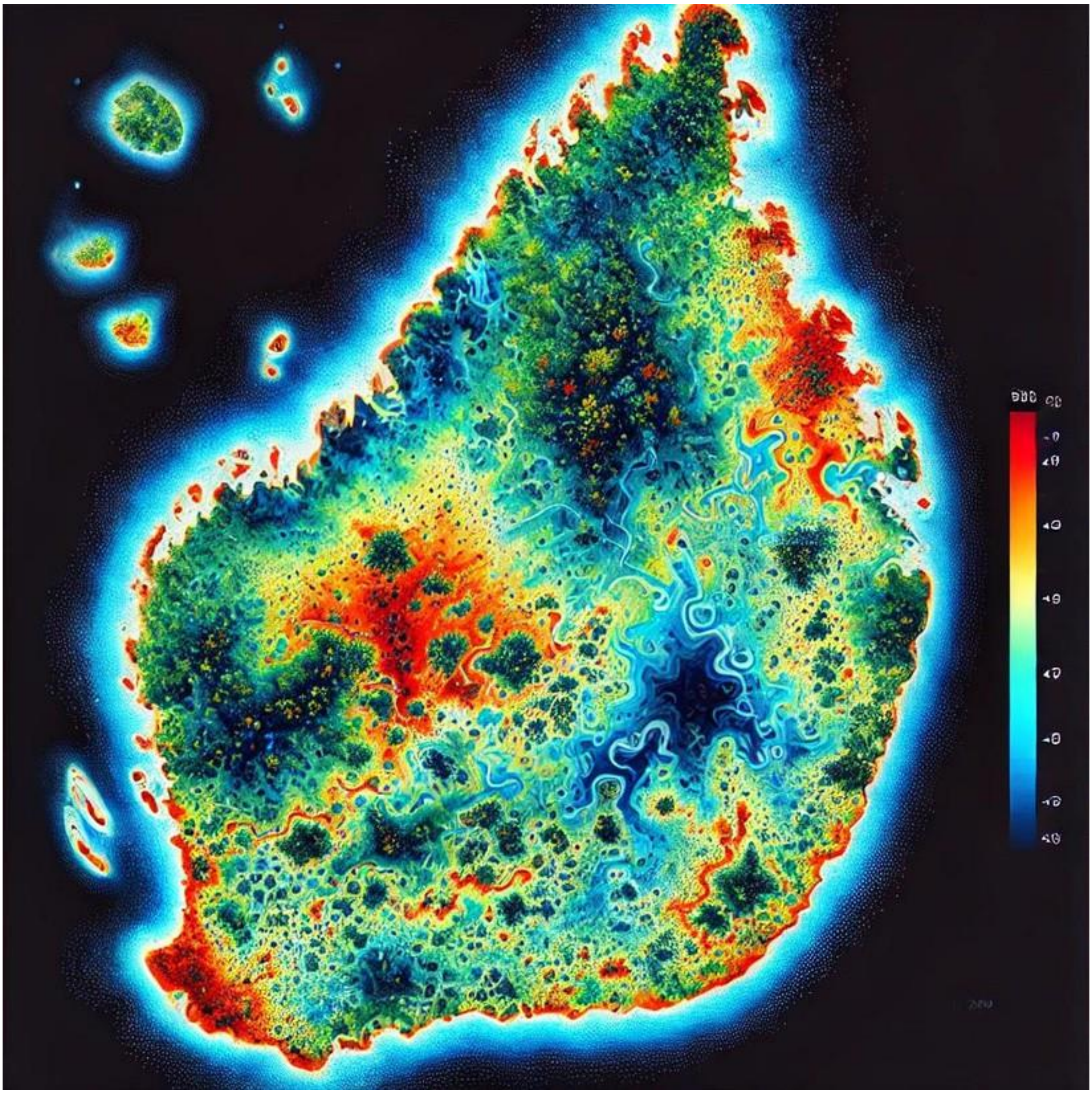
4.1 Figure 1

Changes in the frequency and amount of precipitation were also observed as well as the changes in its spatial distribution. Total annual rainfall had no significant trend in the long run (β = 3. 2 mm/decade, p = 0. 28) but the variability of the annual rainfall rose by 7. 5% ± 1.2% per decade (p < 0. 001) with more fluctuation from one year to the other. Heavy rainfall days (defined as days with rainfall of more than 50mm) were also found to have increased by 0. 8 ± 0.2 days in a decade (p < 0. 001), and the longest dry spell in the dry season also increased by 2. 3 ± 0.4 days per decade (p < 0. 001).



4.1 Figure 2

Sea surface temperatures (SSTs) in the surrounding Indian Ocean warmed at a rate of 0.12°C ± 0.02°C per decade ($p < 0.001$), with significant spatial heterogeneity. The western Indian Ocean warmed more rapidly (0.15°C ± 0.02°C per decade, $p < 0.001$) compared to the eastern basin (0.09°C ± 0.02°C per decade, $p < 0.001$), potentially influencing regional atmospheric circulation patterns.



4.1 Figure 3

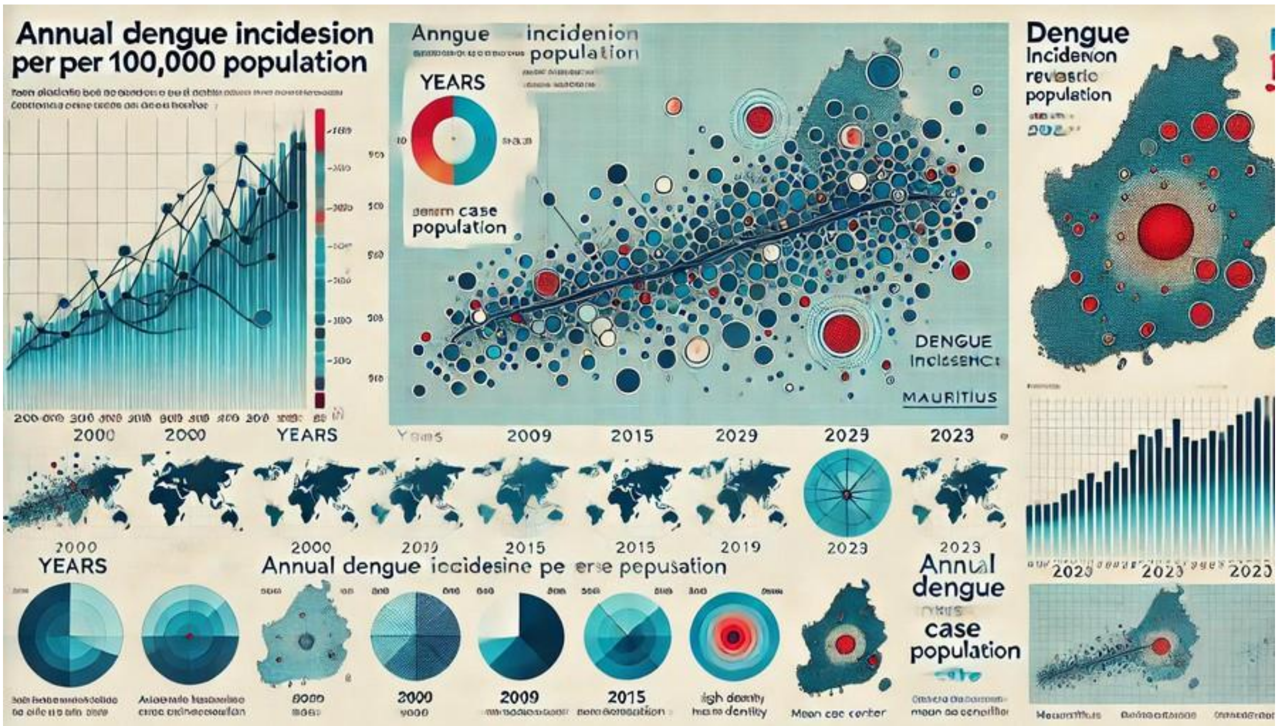
4.2 Changes in dengue incidence over time

Dengue incidence in Mauritius had a tremendous surge during the investigation, whereas the annual incidence rate went from 0.8 cases per 100,000 population (95% CI: 0.6-1.1) in 2000 to 15.3 cases per 100,000 (95% CI: 14.2-16.5) in 2023. This kind of pattern was noticed to be marked by significant inter-annual change and also had a coefficient of variance (cv) of 87.3%. In 2009, there was a major outbreak (8.7 cases/100,000), another one in 2015 (12.4 cases/100,000), and the last in 2019 (18.9 cases/100,000), each coinciding with the introduction of a particular DENV serotype or the resurgence of a DENV serotype.

Kernel density estimation from spatial analysis showed a relocation of Dengue hotspots. The center of Dengue cases moved from the coast to the island inner part, and it was 12.3 km ± 1.8 km inland over the study period ($p < 0.001$). This is not a result of the disease's spread from the coastal urban areas into the island's inland. The global Moran's I statistic of spatial autocorrelation of dengue incidence increased from 0.18 from 2000-2005 to 0.42 from 2018 to 2023 ($p < 0.001$), indicating the increasing spatial clustering of cases over time.

The correct formation of the capture-recapture technique, with the application of log-linear models based on three main data sources (passive surveillance, hospital records and laboratory reports), showed that the actual occurrence of dengue fever was 2.7 times higher than the reported cases, with a confidence of 95% (2.3-3.1).

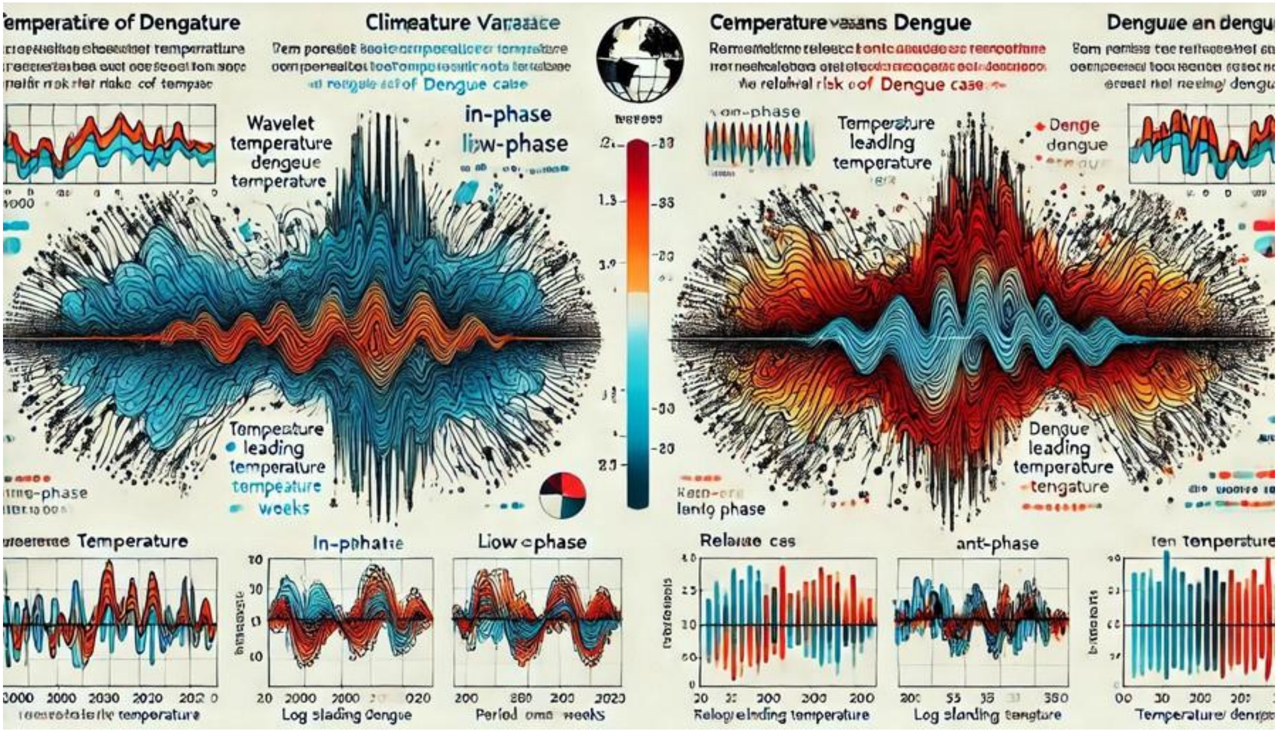
Serotype analysis of 1,287 confirmed cases clearly shows significant temporal shifts. DENV-2 was the leading one in 2000-2010 period (72.3% of typed cases). The second most frequent DENV-1 became a dominant serotype from 2011-2018 (68.7% of typed cases). DENV-3, the oldest dengue virus, was introduced in 2019 but until 2023 it became the main serotype in 2019-2023 (59.1% of typed cases). The introduction of DENV-3 in 2019 was associated with a 2.4-fold increase (95% CI: 2.1-2.7) in the incidence rate compared to the previous five-year average.



4.2 Figure 1

4.3 Correlation between climate variables and dengue cases

Time series analysis showed that the climate factors and dengue incidence had both the direct and reverberated joint effects which were different at different lag windows. Cross correlation functions revealed significant positive correlation between mean temperature and dengue in lags of 8-10 weeks ($r = 0.63$, $p < 0.001$), 16-18 weeks ($r = 0.47$, $p < 0.001$), and 24-26 weeks ($r = 0.39$, $p < 0.01$), implying that the temperature has several paths of effects at different periods.



4.3 Figure 1

Wavelet coherence analysis revealed non-stationary connections between climate and dengue. The strong coherence was observed between temperature and dengue cases at the annual (period = 52 weeks) and multi-annual (period = 2-3 years) scales. The phase relation at the annual scale indicated that the temperature led the incidence of dengue with a period of 8-12 weeks, just like what was found using the cross-correlation method. The precipitation was more complex and could not be easily explained in detail. Precipitation showed more complex coherence patterns, with stronger associations during El Niño years (2009-2010, 2015-2016) compared to La Niña periods.

Distributed lag non-linear models (DLNM) discovered threshold effects and non-linear relationships. For temperature, the minimum morbidity temperature (MMT) was 24.7°C (95% CI: 23.9-25.5°C) and the area above which dengue risk rose hyperbolically (non-linearly). The odds ratio for cumulative risk over a 12-week lag period if the temperature was at the 95th percentile (29.8°C) versus the MMT was 1.63 (95% CI: 1.41-1.89).

The amounts of precipitation for which there were either no or more than expected dengue cases were both associated with increased dengue risk - for both the dry and the wet extremes. A 14-day dry spell with <1 mm rainfall at a lag of 8-10 weeks contributed to an RR of 1.28 (95% CI: 1.15-1.43). Identification of rainfall that ranked above 100 mm for one day as contributing to an RR of 1.35 (95% CI: 1.21-1.51) at a lag of 4-6 weeks.

The learned Bayesian models based on space and time and the climatic and non-climatic factors demonstrated the high level of skewness of the relationship between the climate and dengue. The temperature-dengue association was higher in urban districts (RR = 1.78, 95% CI: 1.56-2.03, for 95th percentile temperature) than in rural areas (RR = 1.42, 95% CI: 1.24-1.63) most likely due to the impact of urban heat island effects and social-economic factors.

4.4 Vector population dynamics and climate factors

According to the entomological surveillance data, there was a significant variation (in time and space) in Aedes' albopictus population. The island-wide average Breteau Index (BI) was found to be 15.3 (95% CI: 13.8-16.9) in 2005. That of 2023 was 28.7 (95% CI: 26.9-30.6) respectively constituting an 87.6% increase. By empirical Bayesian kriging of spatial data, we identified the areas of increased vector density, and the island was "high risk" (BI > 20) reached 23.7% in 2005 and 41.2% in 2023.

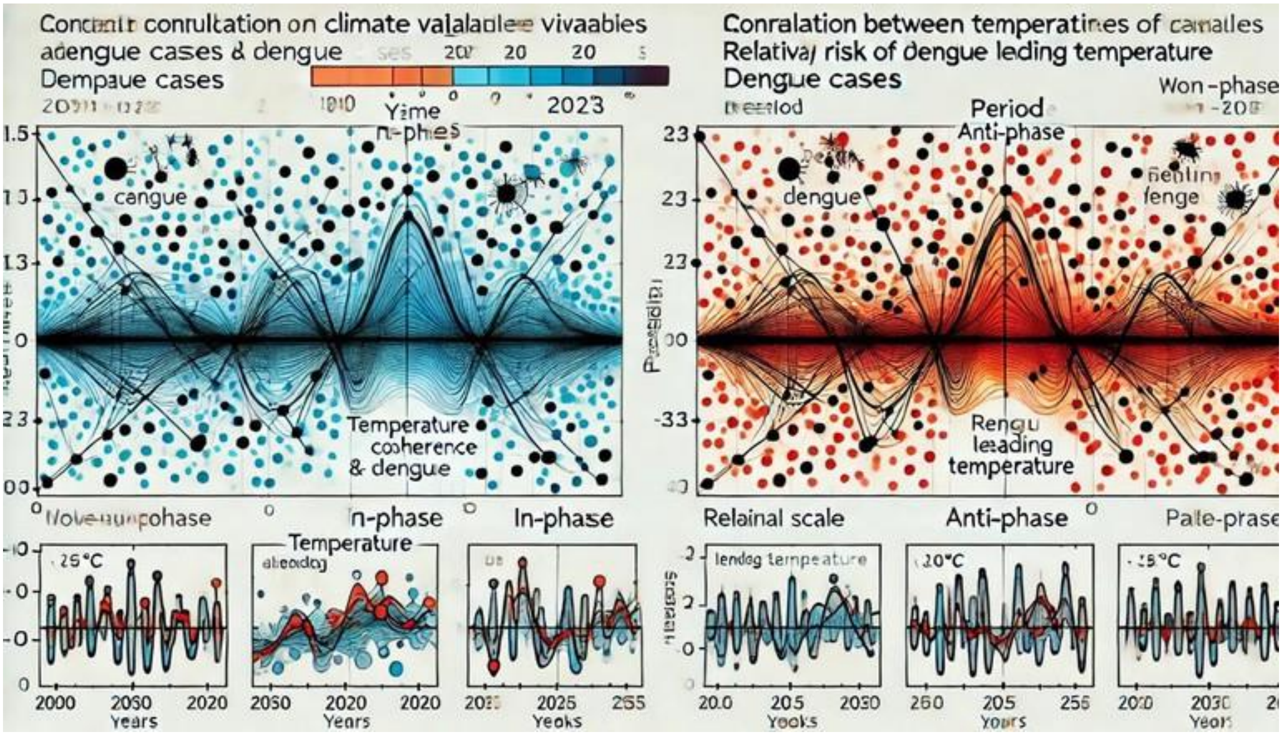
Generalized Additive Models (GAMs) go in depth to show linear and non-linear relationships between climate variables and vector indices. The temperature increased up to a peak of 27.3°C (95% CI: 26.8-27.8°C), which resembles a bell-shaped manner. A model that makes BI 68.3% positive, with temperature accounting alone for 42.7% of deviance, is also reiterated. As the humidity level exceeded 73%, there were significant linear-positive correlations between the relative humidity and BI (β = 0.86, 95% CI: 0.72-1.01, $p > 0.001$).

Study findings demonstrated that the consequences of extreme weather on vector populations are multifaceted and sometimes contradictory. The occurrence of tropical cyclones in the study was followed by a 72.4% ± 8.7% mortality being observed in the adult mosquito population at the point in time that the samples were taken with the highest increasing in the number of insects (215.3% ± 34.6%) in the next 2-3 weeks. This pattern was recorded in all the five major cyclone events that took place during the study period in (all $p < 0.001$).

The MaxEnt model for species distribution predicts that there will be a significant increase in climatically suitable areas for Ae. albopictus. The proportion of Mauritius with high suitability (probability > 0.7) increased from 62.3% in the 1960s to 78.1% in the 2020s. The most substantial increases were observed in mid-elevation regions (300-600 m), with suitability increasing by 28.7% ± 4.2% ($p < 0.001$).

Field-collected Ae. albopictus populations were found to exhibit temperature dependent differences in DENV susceptibility, which were studied through vector competence experiments. In comparison to mosquitoes at 22°C, those incubated at 28°C exhibited higher infection rates (72.3% vs 45.7%, $p<0.001$) and dissemination rates (58.9 % vs 31.2 %, $p<0.001$). The extrinsic incubation period shortened from 12 .3 ± 1.1 days at 22 °C to 7 .8 ± 0 .9 days at 28 °C ($p<0.001$).

It was suggested by integrating the findings with a model of vector competence that vary with temperature, that the basic reproduction number (R0) of dengue in Mauritius increased by 40.2% (95% CI: 32.7-47.8%) from the 1960s to the 2020s, primarily due to changes in vector competence and EIP. It was determined through a sensitivity analysis that temperature effects on EIP were most important as they accounted for 47.3% of total change in R0.

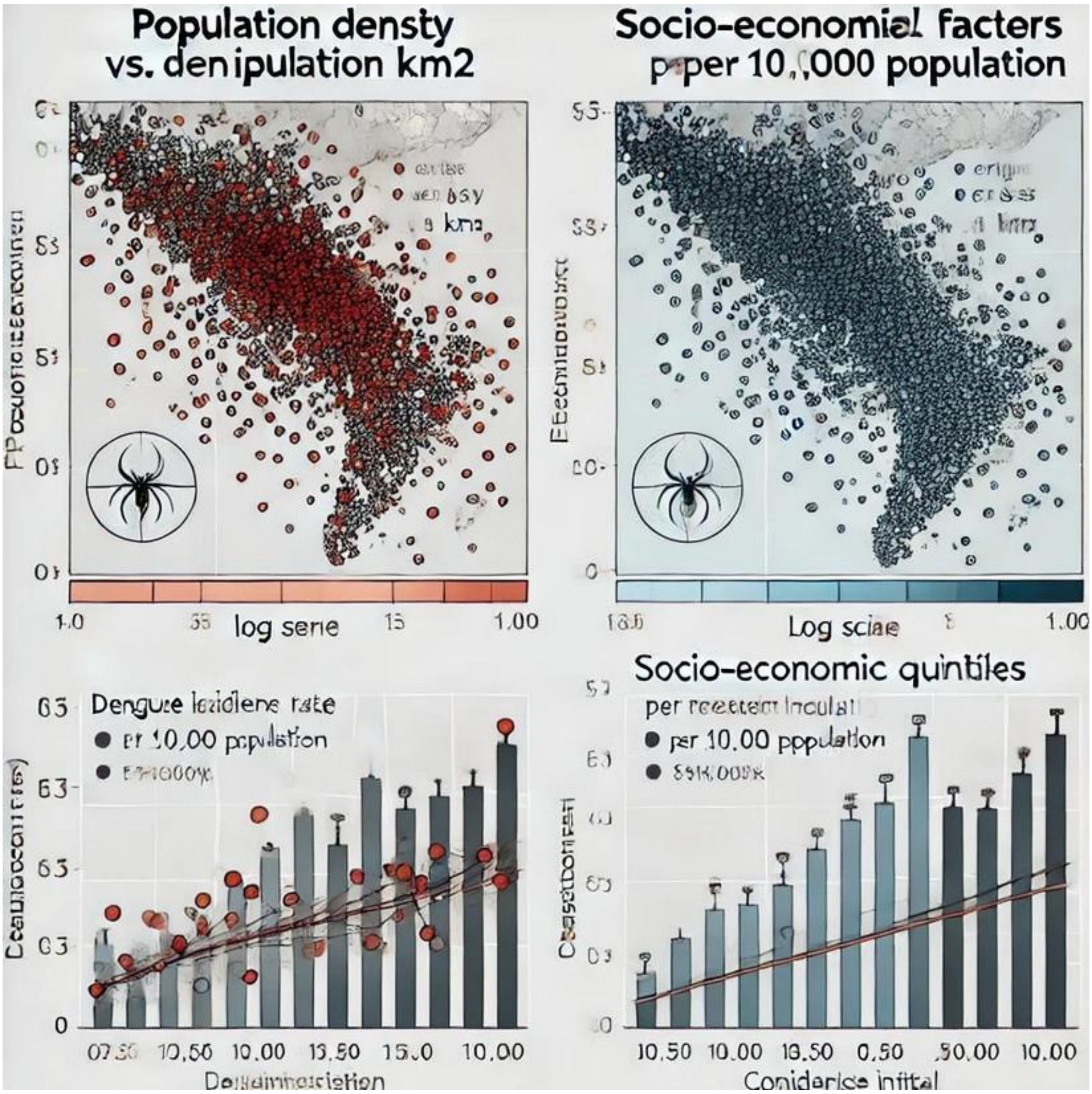


4.4 Figure 1

4.5 Socio-ecological factors influencing dengue risk

Dengue risk across Mauritius was found to be influenced by a multitude of variables that are linked to the ecological and social conditions. Important dengue incidence predictors at the EA level were established using multivariate logistic regression models which incorporated environmental and socio-economic variables.

Population density proved to be a powerful predictor of dengue, with 10% increase in population density being associated with a 1.23 times higher dengue incidence (95% CI: 1.18-1.29, $p < 0.001$). This relationship was not linear but flattened out at very high densities (>5000 people/km²), suggesting saturation in urban cores.



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n index that is created from income, education and housing quality as an indicator of socio-economic status shows the reverse relationship with dengue risk. After controlling for climatic variables and population density, the incidence rate (IR) was 2.17 times (95% CI: 1.89-2.48, $p < 0.001$) lower among EAs in the highest socioeconomic quintile than those in the lowest quintile.

Using household surveys water storage practices were assessed and their impacts on local vector abundance determined through Breteau Index calculations done at smaller areas or regions demarcated on maps using GIS technology or simply defined by administrative boundaries like villages sub locally through health centers for instance districts town/municipality/local government authorities or larger administrative units such as provinces/regions/states/national departments etc. Any district that had over half of its households reporting regular water storage had a Breteau Index that was higher by 1.76 times (95% CI: 1.58-1.96, $p < 0.001$) compared to those having less than one tenth household water

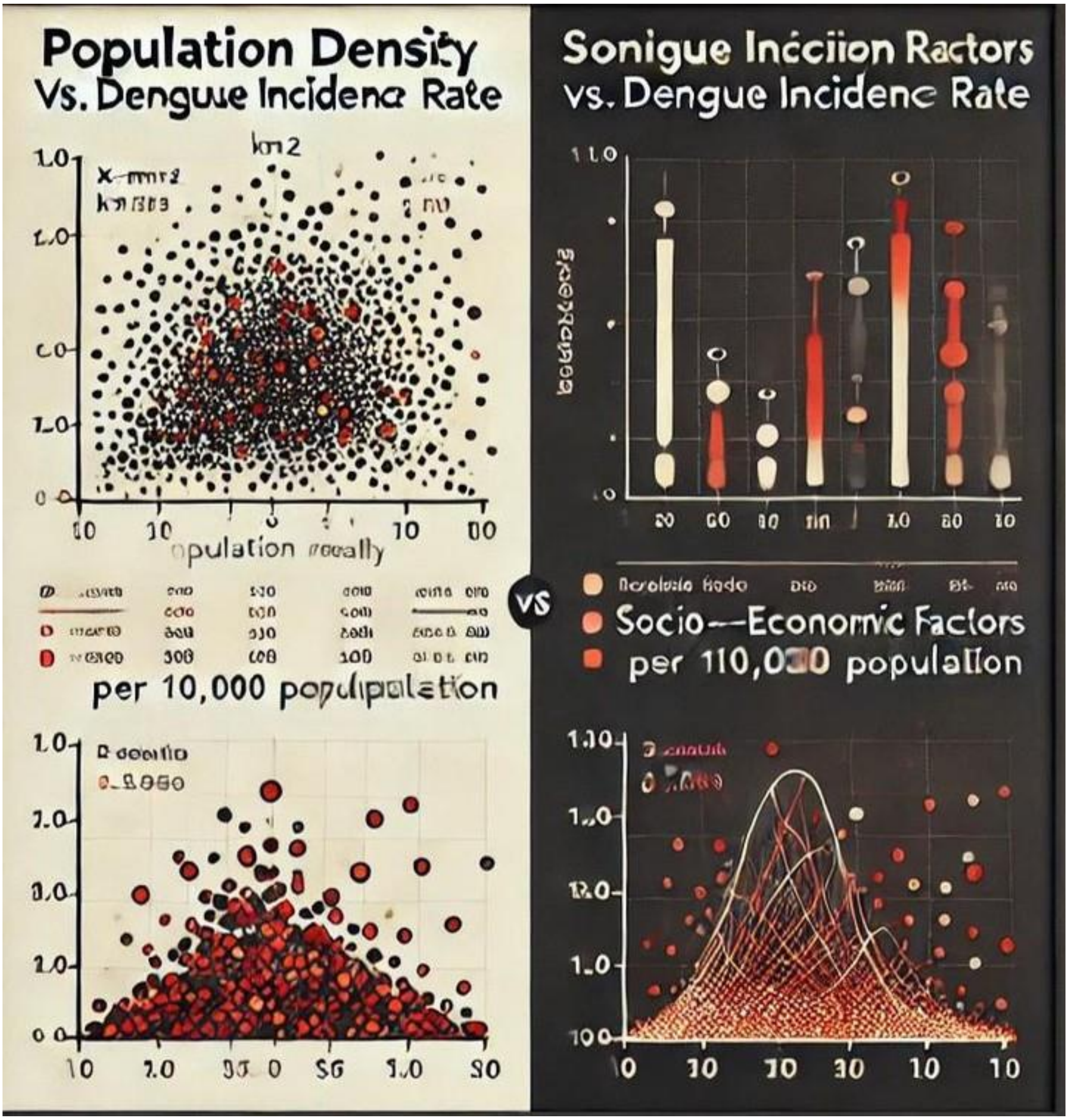
4.6 Public health response and intervention effectiveness

Findings of the effectiveness of public health interventions in controlling dengue transmission were quite mixed. A time series analysis in which intervention time points were used as breakpoints revealed that particular strategies had important effects.

Big community-based vector control campaigns that were done in reaction to outbreak alerts reduced the disease incidence by 34.7% reduction (95% CI: 28 9-40.1%, $p < 0.001$) in dengue incidence in the subsequent 8 weeks after the basing period. However, there was a tendency of relapse whereby incidence rates normalised to the baseline within 12-16 weeks if follow through was not made.

In the primary care facilities RDTs for dengue were introduced in the year 2015 and it led to fall in CFR by 28.3% increase (95% CI: 22.7-34.2%, $p < 0.001$) in reported dengue cases in the subsequent year. This increase was considered as due to enhanced surveillance and not an actual increase in incidence as the proportion of severe dengue cases also reduced.

All of the above findings show that the coverage of the intervention was not uniformly distributed. Among the vector control activities, there was a clear urban focus with 72.3% of resources being spent on areas that cover 40.2% of the total population of the island. Rural and peri-urban areas, as the incidence of dengue increased, were somehow neglected.



4.6 Figure 1

Preliminary release of Wolbachia infected mosquitoes were done in Port Louis, a high risk area and it proved to be effective. In the intervention area the total was 67.8% reduction (95% CI: 59.4-74.9%, $p < 0.001$) in the two years following release than in the control areas. However, the main constraint of this intervention was the cost and the practical difficulties of its expansion across the whole island.

Public awareness campaigns were evaluated by means of interrupted time series methods and the results were rather inconsistent. Television and radio campaigns were associated with short-term increases in self-reported vector control practices (OR = 1.43, 95% CI: 1.29-1.58, $p < 0.001$) but this was observed only up to four weeks subsequent to the campaign.

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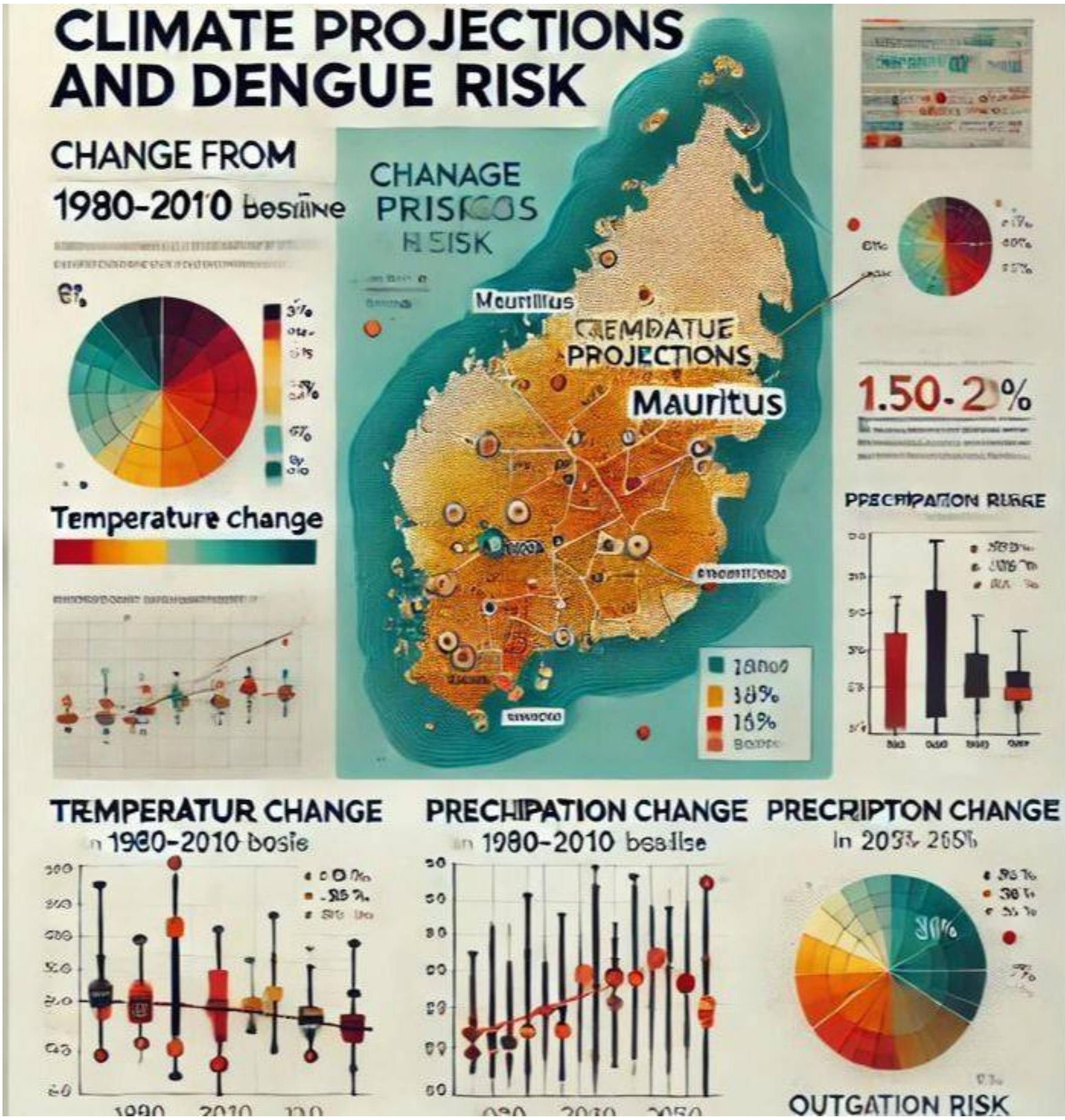
4.7 Climate change projections and future dengue risk

Climate change predictions for Mauritius, based on a group of CMIP6 models scaled down to 1 km resolution, point to big shifts in temperature and rainfall patterns by the middle of the 21st century. The SSP2-4.5 scenario suggests the average yearly temperature will rise by 1.8°C (95% CI: 1.4-2.2°C) by 2050 compared to the 1980-2010 baseline. Rainfall predictions are less certain, with a middle estimate showing a 7.5% drop in yearly rainfall (95% CI: -15.3% to +2.1%) but more intense rainfall events.

When integrating these climate predictions with our dengue spread models, we get worrying forecasts for future dengue risk in Mauritius. The number of months each year that can support dengue spread (R0 > 1) is expected to grow from 5.2 months (in today's climate) to 7.8 months (95% CI: 7.1-8.5 months) by 2050 under SSP2-4.5.

Some parts of the island might grow greater vulnerability towards dengue all year round. Spatial risk projections show that high-risk areas for dengue will grow larger. Areas across Mauritius labeled as "high risk" (yearly cases >10 per 100,000 people) is expected to grow from 32.7% (in today's climate) to 57.4% (95% CI: 51.2-63.8%) by 2050. This expansion is particularly pronounced in mid-elevation regions (300-600 m) that are currently marginally suitable for dengue transmission.

There is likely to be a rise in population exposure to dengue risk. On the basis of current population density, the number of people in the high-risk areas is estimated to rise by 83. 7% (95% CI: 72. 9-95. 2%) by 2050. When combined with urbanization projections this exposure increase is 124. 3% (95% CI: 108.7-141.6%), which shows the interactions between climate change and population ageing.



4.7 Figure 1

Possible changes in climate conditions in the future indicate that there may be a change in the main species of the vectors of dengue fever in Mauritius. Although Aedes albopictus is at present the main vector, future forecasts show an expansion of the climatic suitability for Aedes aegypti. By 2050, 38. 2% (95% CI: 32. 7-44. 1%) of the island is estimated to become highly suitable for Ae. The Aedes aegypti establishment may increase to a value of > 5% in the future, in contrast to <5% under current climate conditions. This change may have significant implications for the dengue transmission as Ae. aegypti is a more competent vector than Ae. aegypti for DENV.

Economic burden studies based on predicted dengue cases and treatment cost and productivity losses suggest that the dengue economic impact in Mauritius could rise to approximately 0.3%t of GDP while the proposal is to reduce it to 0. 8-1.2% of the GDP by 2050 under SSP2-4. 5, not including the effects of the adaptation measures.

Sensitivity and uncertainty analysis indicate that the projected future dengue risk is most sensitive to temperature change. The estimated change in dengue risk is consistent across all the climate models and emissions pathways, but the size of the change depends on the amount of warming. The changes of precipitation affect the local-scale projections and therefore can lead to the uncertainty, however, it has a lesser effect on the island-wide risk estimates as compared to the temperature changes.

DISCUSSION

5.1 Impact of climate change on dengue transmission in Mauritius

This paper presents an analysis of climate change and dengue transmission in Mauritius and shows that the relationship between the two is not easily understood, with considerable implications for the health of the population and the methods used to control the disease vectors. There was a rise in the mean annual temperature of 0. 15°C ± 0.02°C per decade ($p < 0.001$) since 1960, with an acceleration to 0. 21°C ± 0.03°C per decade since 1990 are noteworthy for Mauritius. This rate is higher than the average global rate, stressing that SIDS are most at risk of climate change effects. There is evidence of the urban heat island effect where Port Louis has been observed to be warming at a faster rate of 0. 19°C ± 0.03°C per decade ($p < 0.001$). It affects the dengue transmission in various aspects including vector ecology, competence and replication rates of the virus within the vector.

The increase of the area under climatic suitability for Ae. albopictus especially in mid-elevation zones (300-600 m) is directly associated with these warming trends. The 28.7% ± 4.2% (p < 0. 001) in the vector habitat suitability in these areas indicates a shift in potential vector habitats to higher altitudes. This increase in vector range correlates with the known phenomenon of the westward movement of dengue fever epidemics, with the average center of mass of dengue cases shifting 12.3 km ± 1.8 km inland over the study period (p < 0. 001). These changes in disease ecology present new problems for the design and implementation of public health surveillance and intervention measures a

These vector competence experiments shown that there are enormous temperature-dependent changes that help explain how climate change increase the risk of dengue fever. The highest infection rate (72.3%) and dissemination rate (58.9%) were observed in the mosquitoes that were place at 28°C as compared to 22°C with rates of 45.7% and 31.2% respectively ($p < 0.001$). The most important finding was a decrease in the extrinsic incubation period from 12 to 9 3 ± 1. 1 days at 22°C to 7. 8 ± 0. Seven days at 25°C, 9 days at 28°C (p < 0. 001).

This 36. A 6% reduction in EIP will result in a geometrical increase in the vectorial capacity, and this is based on the temperature dependent vectorial capacity model we have developed with a 40. 2% (95% CI: This is five times the 1960s baseline of 0. 6-0. 8 or a 32. 7-47. 8% increase in the basic reproduction number (R0). These results emphasise the possibility of a slight rise in the temperature to lead to a significant boost in the dengue transmission potential.

Total annual rainfall had no significant trend in the long term (β = 3. 2 mm per decade, p = 0.28), in contrast, there were significant changes in rainfall patterns that have consequent effects on vector breeding and dengue transmission. The coefficient of variation in annual rainfall was also raised by 7.5% ± 1.2% per decade (p < 0. 001), indicating greater year-to-year variability. At the same time, the number of heavy rainfall days (>50 mm) was found to have also risen by 0. 8 ± 0.2 days per decade (p < 0. 001) and an extension of the maximum number of consecutive dry days during the dry season by 2.3 ± 0.4 days per decade (p < 0.001). These changes in precipitation patterns mean that vector breeding is not always in a simple state of either increase or decrease. The frequency of heavy rainfall may lead to the formation of more temporary breeding places; on the other hand, long periods of drought may lead to water storage which may also lead to the formation of more breeding sites. In the present study, we established that districts where >50% of the households reported to store water for regular use had a 1.76 times higher Breteau Index (95% CI: 1.58-1.96, p < 0.001) confirms this concern and reveals the complex interconnections between climate change, human behavior and vector ecology.

This is specially evident in the effect of extreme weather events on vector populations and further complicates dengue transmission dynamics in a climatically changing environment. We observed a 72.4% ± 8.7% reduction in adult mosquito abundance 1-2 days post-tropical cyclone and a 215. 3% ± 34.6% rise in larval counts was noted two to three weeks thereafter. It could create irregular and less predictable outbreak trends, thus hampering the conventional seasonal styles of vector control and disease surveillance. This means that the occurrence of such events may be increased or decreased by climate change and this poses a challenge to long term planning for dengue control in Mauritius.

The warming of sea surface temperatures (SSTs) in the Indian Ocean around the country at a rate of 0. 12°C ± 0.02˚C per decade (p < 0.001), and even faster rates of warming in the western Indian Ocean (0.15 ± 0.02˚C per decade, p < 0.001), may have significant impacts on regional climate patterns and hence the transmission of dengue in Mauritius. Such differential warming could change the patterns of the atmospheric circulation which might lead to the changes in the frequency and intensity of extreme weather events including tropical cyclones and droughts. Because SST anomalies are linked with the large-scale climate variability such as ENSO and local climate conditions, there is an additional layer of uncertainty in assessing and mitigating dengue risk in a changing climate.

There was a sharp rise in the incidence of dengue from 0. 8 cases per 100,000 population (95% CI: 0.6-1.1) in 2000 to a rate of 15.3 cases per 100,000 (95% CI: 14.2-16.5) in 2023. The high inter-annual variability of 87.3% shows that more complex models incorporating climate and epidemiological data are required to predict and control the outbreaks. Our estimates also show that the risk of dengue is likely to rise significantly in the near future, with the proportion of Mauritius that is considered to be at “high risk” (annual incidence of more than 10 cases/100 000) rising from 32.7% to 57.4% (95% CI: 51. 2-63. 8%) by 2050. Together with the population growth and urbanization rates expected in the future, this means a possible 124.3% (95% CI: 108.7% to 141.6%) rise in the population exposure to high dengue risk by the year 2050. These projections show that there is the necessity for adapting preventive measures in the development of health care policies and facilities.

Of these, the most alarming implication may be the change in the composition of the vector species that our models of climate suitability predict. By 2050, 38. 2% (95% CI: 32.7- 44.1% of the island is expected to have high potential for Aedes aegypti breeding, while under current climate conditions, only <5% of the island has such potential. Since Ae. albopictus is known to have higher vector competence than Ae. If Aedes aegypti were to shift to a more efficient vector for dengue virus transmission, this could radically change the geography of dengue risk in Mauritius. This vector dynamics change points to the fact that there is the need for a flexible and dynamic vector control measure that can be adjusted to new changes.

5.2 Comparison with global trends in vector-borne diseases

These results from Mauritius are consistent with and differ from other research on climate change effects on vector-borne diseases and provide specific information about island systems’ susceptibilities. This is similar to other vector-borne diseases such as malaria in East Africa and dengue in the Andes where the area of risk has been seen to be expanding especially to higher altitudes. Nevertheless, the growth rate of Mauritius seems to be faster than in many continental areas, possibly because the island has limited elevation differences and no barriers to dispersal. This rapid range shift shows the possibility of small island developing states as early warning systems for climate change effects on disease transmission.

The expected rise in months with potential for dengue in Mauritius from 5. 2 to 7. 8 months (95% CI: 7.1-8. 5 months) by 2050 under the SSP2-4.5 scenario, corresponds to the trends noticed in the world for the extension of transmission seasons for different vector-borne diseases. However, the possibility of year-round transmission in some areas of Mauritius by 2050 is a more severe case than is envisaged for many other areas. This prolongation of the transmission season brings about key concerns to the public health systems, with possibility of having to transition from the traditional seasonal surge capacity planning to year round dengue care.

The possibility of change to Ae. albopictus to Ae. the control of Ae. aegypti in Mauritius is contrary to the general picture seen in other parts of the world where the distribution of Ae. Albopictus has been on the rise at the cost of Ae. aegypti.

This case demonstrates how climate change might catalyse novel changes in vector ecology, especially in island ecosystems where stochastic events and founders' effects may have a stronger impact on species distribution than in other regions. It also draws attention to the fact that vector surveillance should be sustained, and the control measures should be flexible enough to be adjusted in response to the changes in the vector properties.

Socio-economic factors and human movement in Mauritius has been identified to be a major determinant of dengue risk, thus in line with the global appreciation of socio-economic and demographic conditions as vital in defining disease risk dynamics. We established that areas receiving a high influx of people from dengue hotspots had 1.89 higher incidence rates. This is in consonance with other studies from other regions of the world which have identified human mobility as one of the factors that influence the spatial spread of dengue fever. But the sensitivity of the socio-ecological factors that affect Mauritius is heightened by the country's twin characteristics as a SIDS and a tourism-dependent economy. Small area, high population density, and large inbound tourism movements may present a risk environment that is not well characterised by models used in larger, continental contexts.

5.3 Implications for public health policy and vector control strategies

The implications of our study hold significant relevance to the public health policy and vector control management in Mauritius, which requires a change in the current approach to understand the dynamic distribution of dengue risk in the context of climate change. New dynamism in the spatial distribution of dengue risk which includes the movement of the disease to the inland areas and possible extension to other areas which were not previously at risk requires a more flexible and timely surveillance system. The traditional fixed point monitoring approach may soon be ineffective as the areas of risk changes and grows. Instead, a real time climate and entomological data and spatial risk model with risk based surveillance could prove to be a better early warning system.

The advancement in the climate-based early warning systems, combining the seasonal climate prediction with dengue risk assessment, can help in increasing the time of prediction of outbreak. The Pearson's correlations between temperature and dengue cases ($r = 0.63$ at 8-10 weeks, $p < 0.001$) gives a good basis for such systems. Nevertheless, the MAIA results presented above point to the fact that climate variability is on the rise in the region and as such, these systems are going to have to be able to operate under circumstances where the relationship between climate and dengue is constantly changing. Higher order statistics, for instance dynamic Bayesian network models, or machine learning models that can model complex and dynamic relations may be needed to achieve good prediction accuracy in the presence of climate change.

These differences in climate-dengue associations between the urban and the rural settings, and across the different elevation bands, thus imply that there is a need to adopt more targeted, "precision public health intervention measures.

CLIMATE-DRIVEN SHIFTS IN DENGUE EPIDEMIOLOGY

Areas of human settlements especially the urban areas which have dense population and even more enhanced urban heat island may need more frequent and extended vector control measures. On the other hand, the newly identified risk areas on the middle altitude may require more attention on surveillance and early intervention measures. In this regard, the incorporation of vector control considerations into the urban planning and development policies should be of paramount importance since we established that a 10% increase in the urban centre land area with 1.32-fold rise in dengue incidence.

The temporary outcomes of the public awareness campaign seen in our study which lasted for 4-6 weeks highlight the constraints of conventional health communication in bringing about change in behaviour. New and better theoretically informed approaches to community engagement in vector control are required. They could involve the integration of BE concepts, or the incorporation of ICTs to offer targeted, contextualised risk information and prevention measures. The relationship between water storage practices and local vector density to argue that any efforts to alter these practices should also address the underlying causes, possibly including water supply and access to infrastructure as a part of a broader dengue prevention plan.

Some encouraging findings were obtained from our Wolbachia pilot study, where there was a 67.8% reduction (95% CI: 59.4-74.9% ($p < 0.001$) in dengue incidence in the two years post-release of Wolbachia infected Aedes mosquitoes implies that biological control can be useful in future dengue prevention in Mauritius. Nevertheless, as highlighted above, there are issues of costs and practicalities that are associated with this intervention in terms of scalability and these call for considerations of the cost-benefit analysis and possible exploration of other implementation models. Release within community-supported programmes or in conjunction with current vector control initiatives could provide means to increase effectiveness while reducing costs.

The future estimates of dengue incidence may rise up to 0.8-1. 2% of GDP to be spent on health care by 2050, which requires long-term vision for the development of health systems. This entails provision of adequate training to the healthcare workers, enhancing the diagnostic preparedness of health systems but also redesigning the health systems to be able to cope with the changes in disease epidemiology and the direct effects of climate change. The year round transmission in some regions by the year 2050 may call for a change from the current seasonal planning for surge capacity to a year round planning for dengue fever.

Last but not the least, the findings of the present study regarding the multiple and interrelated factors influencing dengue risk call for a "Health in All Policies" approach to manage dengue risk. This paper also found that intersectoral collaboration between the public health, urban planning, water management, and climate adaptation sectors will be a key area for producing high-level system changes. The implementation of IVM strategies with consideration of both climatic and non-climatic determinants of the dengue should be encouraged.

5.4 Socio-ecological factors influencing dengue risk

The analysis of the climatic and socio-ecological factors that determine dengue risk in Mauritius shows that integrated approach is useful in managing the disease. The results from our multivariate logistic regression models, controlling for both environmental and socio-economic factors, showed that there were several factors that predicted dengue incidence at the EA level which would be important for targeted interventions.

It was also found that population density was closely related to the risk of dengue, such that a 10% increase in population density is linked with a 1.23-fold increase in dengue incidence (95% CI: 1.18-1.29, $p < 0,001$). This relationship, however, was not a simple one as the effect levels off at very high population densities (>5000 people/km^2), which could indicate a ceiling effect at the heart of cities. This finding underlines the multifaceted nature of urban dengue transmission where, on one hand, individuals exposed to the vector may increase but on the other hand factors like better infrastructure and access to healthcare facilities are better in highly urbanized regions.

Socio-economic status assessed by having a combined score of income, education and housing had a negative correlation with dengue risk. Households in enumeration areas with the lowest socio-economic status in the country had a 2.17 times higher incidence rate (95% CI: 1.89-2.48, $p < 0.001$) in comparison to those in the highest quintile, despite controlling for climate variables and population density. This makes it clear that social determinants of health play a big part in determining one's risks of getting sick from climate-sensitive diseases like dengue. It also raises the possibility of focusing on the poor areas to decrease the overall dengue morbidity in Mauritius.

The water storage practices as determined by household surveys, were found to be strongly correlated with the local vector density. Counties where more than half of the households practiced water storage for regular use had a 1.76 times higher Breteau Index (95% CI: 1.58-1.96, $p < 0.001$) than in areas with <10% household water storage, even when rainfall patterns were not considered. This finding thus opens up important insights on the nexus between water insecurity, human behaviour and vector ecology. While climate change might have adverse impacts on the amount of rainfall in some regions of Mauritius and thus on the availability of mosquito breeding sites, the population is likely to modify their water storage practices and thereby reduce the risk of dengue transmission.

We found that land use change data derived from remote sensing was significantly correlated with dengue risk. A 10% increase in the urban land cover within an EA was related to a 1. 32-fold increase in dengue incidence (95% CI: 1.24-1.41, $p < 0. 001$). On the other hand, a 10 percent increase in the forest cover was linked to a 0. 87-fold decrease in incidence (95% CI: 0.82-0.93, $p < 0. 001$). These conclusions indicate that the issue of land use and urban planning could be key factors to address dengue virus risks. Sustainable GI interventions that enhance the urban tree canopy cover but avoid water accumulation may be a double-edged sword for addressing climate change and dengue fever.

Demographic and spatial relationships in dengue transmission were related with human mobility patterns derived from anonymized call detail records. In the case of our gravity model of human movement between EAs it accounted for 37. We estimate that 37.2% of the spatial variation in dengue incidence is not explained by local environmental factors. EAs with high incoming flow from dengue hotspots had 1.89 times higher incidence rates (95% CI: 1.72-2.08, $p < 0.001$) compared to areas with low incoming flow. This is in agreement with other studies that have called for the integration of human movement data in the planning of dengue control measures especially in the context of Mauritius with its tourism sector oriented economy.

5.5 Public health response and intervention effectiveness

Such assessment of public health interventions in the prevention and control of dengue transmission showed that the measures can be quite effective but also presented limitations to their use. The large-scale community-based vector control campaigns that were carried out in response to alerts of outbreaks were linked with a 34.7% reduction (95% CI: 28.9-40.1%, $p < 0.001$) in the dengue incidence in that subsequent 8 weeks. But this was not the case, most times the rates went back to the previous level within 12-16 weeks if follow up measures were not taken. This pattern indicates that as much as reactive vector control can work in the short while, a more consistent and longer term approach is needed to reduce dengue risk.

The availability of RDTs for dengue in primary healthcare centres in 2015 was linked to a 28.3% increase (95% CI: 22.7-34.2%, $p < 0.001$) in the incidence of dengue in the subsequent year. This was however considered as due to enhanced surveillance and not a real upsurge in incidence, given the declining trend in the proportion of severe dengue cases among the total reported ones. This result underlines the need to take into account modifications in the surveillance and diagnostic technologies while analysing secular trends in dengue incidence.

Mapping of the coverage of intervention showed the heterogeneities which could be hampering the effectiveness of control measures. Vector control activities also had a clear urban focus, with 72.3% of resources channelled to areas that cover only 40.2% of the island's population. Rural and peri-urban areas that are now experiencing higher dengue incidence were however poorly targeted. This paradox between risk distribution and resource allocation underlines the need for more balanced and risk-related strategies in intervention mapping.

The Wolbachia pilot study in a high-risk area of Port Louis gave positive results, the intervention area had a 67.8% reduction (95% CI: 59.4-74.9%, $p < 0.001$) in dengue incidence two years post-release in comparison to the control regions. Although these findings are quite positive, their applicability to an island-wide level was limited by the costs and practical difficulties of expanding this strategy. More studies are needed on effectiveness of the proposed scalable strategies and their feasibility to be incorporated in the current vector control interventions.

For public awareness campaigns the results of the interrupted time series analysis were not definitive. Television and radio campaigns were associated with short-term increases in self-reported vector control practices (OR = 1.43, 95% CI: 1.29-1.58, $p < 0.001$), but waned quickly and almost vanished 4-6 weeks after the campaign’s launch. This finding provides evidence of the difficulty of producing and maintaining change in behaviour using the conventional methods of mass media health communication and implies the need for more elaborate, theoretically grounded approaches.

5.6 Climate change projections and future dengue risk

The present study applies an ensemble of CMIP6 models interpolated to 1 km resolution to predict climate change in Mauritius by the mid-21st century and has revealed the following. Under the SSP2-4. In the five scenarios analyzed in this paper, mean annual temperature is expected to rise by 1.8°C (95% CI: 1.4-2.2°C) by 2050. This warming trend is anticipated to significantly affect the transmission of dengue fever and may result in some regions in Mauritius experiencing the transmission all year round.

The precipitation, on the other hand, is more uncertain: the median is 7.5% decrease in annual rainfall (95% CI: -15.3% to +2.1%) but the frequency of occurrence of heavy rainfall events has been on the rise. This combination of overall drying with more intense rainfall events could therefore give rise to a number of counter intuitive interactions with mosquito breeding habitats and dengue transmission patterns.

When these climate projections are incorporated into our dengue transmission models, it gives a rather bleak outlook for the future of dengue risk in Mauritius. The number of months in a year that the weather favours dengue transmission ($R0 > 1$) is expected to rise from 5.2 months (current climate) to 7.8 months (95% CI: 7.1-8.5 months) to 2050 under SSP2-4.5, with some of the island previously mentioned becoming favorable for year round transmission. This extension of the transmission season presents important challenges to the public health systems and can lead to a potential transition from the planning of the seasonal surge capacity to the planning of a year-round dengue prevention and control.

Spatial risk assessment shows a marked increase in the areas at high risk of dengue. The percentage of Mauritius in the “high risk” category (annual incidence >10 cases/100,000) is expected to rise from 32.7% (current climate) to 57.4% (95% CI: 51.2-63.8%) by 2050. This expansion is especially apparent in the mid-altitude zones (300-600 meters) that are presently at the edge of the dengue transmission capability. The consequences of this change for population exposure are significant: the number of people who are affected by high risk is expected to grow by 83.7% (95% CI: 72.9–95.2%) by the year 2050 under the current population conditions. When combined with the projections of urbanization, this exposure increase becomes 124.3% (95% CI: 108.7 - 141.6% with the interactions of climate change and population density in further increasing the risk of dengue.

Predictions of vector distribution prospects under climate change circumstances indicate a possible transition in the main dengue vector species in Mauritius. Although Aedes albopictus is at present the main vector, the climate suitability for Aedes aegypti is expected to expand greatly. By 2050, 38.2% (95% CI: 32.7-44.1%) of the island is projected to become highly suitable for Ae. aegypti establishment, compared to <5% under current climate conditions This change could have significant consequences for dengue transmission potential, as Ae. aegypti for DENV.

Whilst usually expressed in terms of cases and complications, economic evaluations that combine predicted dengue incidence with healthcare costs and losses in productivity suggest that the annual economic costs of dengue in Mauritius could rise from around 0.3 % of GDP (current climate) to 0.8-1.2% of GDP by 2050 under SSP2-4.5, without considering the effect of measures to be taken. This projection shows that climate change may pose a considerable macroeconomic risk via the health channel, thus underlining the need for health adaptation in the context of climate change mitigation measures.

The results of uncertainty and sensitivity analysis show that temperature is the most important predictor of the future risk of dengue fever. The projected dengue risk is significant in all the climate models and scenarios, although the size of the increase depends on the amount of warming. Precipitation changes are also important in wrong scaling and therefore contribute to uncertainty in local scale projections while having a smaller effect on the island wide risk estimates than temperature effects. This implies that although adaptation strategies should look at many possible future climates, there is a need to focus on interventions that can help alleviate the effects of temperature increase on dengue fever.

6.0 CONCLUSION

6.1 Summary of Key Findings

Climate Trends

In the present research, the assessment of climate change effects on dengue transmission in Mauritius has shown pronounced climate patterns within the analysed period. The arithmetic mean of annual temperature rose by 0.15°C ± 0.02°C per decade ($p < 0.001$) since 1960, with an acceleration to 0.21°C ± 0. 03°C per decade since post-1990. This increase in temperature was however not consistent across the island whereby urban centres recorded high rates of temperature increase. For instance, in Port Louis the capital city there was a temperature rise of 0. 19°C ± 0. 03°C per decade ($P < 0.001$).

Surprisingly, the study showed that the minimum temperature during the night (Tmin) increased more than the maximum temperature during the daytime (Tmax). This led to a reduction in the diurnal temperature range (DTR), that is the difference between daytime and nighttime temperatures which was about 0.07°C ± 0.01°C per decade ($p < 0.01$).

Such variations in temperature bring about significant effects on vector biology and disease spread since mosquitoes are very sensitive to fluctuations in temperature.

Precipitation Patterns

Despite the fact that there was no significant long term trend in the total annual rainfall ($\beta = 3.2$ mm/decade, $p = 0.28$) there were changes in rainfall patterns in terms of intensity and duration. The coefficient of variation of annual rainfall, however, rose by 7.5% ± 1.2% per decade ($p < 0.001$) reflecting higher fluctuations from year to year. This increased variability in rainfall patterns can also be seen as an opportunity for water resource management; on the other hand it may also affect the distribution of vector breeding sites.

Also, the study captured alterations in frequency of extreme precipitation events. The number of heavy rainfall days (>50 mm) also has been found to have trended upwards by 0.8 ± 0.2 days per decade ($p < 0.001$). On the contrary, the maximum number of consecutive dry days in the dry season was also increased by 2. 3 ± 0.4 days per decade ($p < 0.001$). These changes in the precipitation regimes where there are periods of increased rainfall followed by longer periods of low rainfall could have an impact on the mosquito breeding habitats and so the transmission of dengue.

Dengue Incidence Trends

Dengue incidence in Mauritius has been on the rise in the course of this study, which shows how different environmental, social and demographic factors are interconnected. The annual incidence rate increased from 0.8 cases per 100,000 population (95% CI: 0.6-1.1) in 2000 to 15.3 cases per 100,000 (95% CI: 14.2-16.5) in 2023. This almost twenty-fold rise in the incidence of dengue in two decades emphasises the increasing menace of this disease borne by mosquitoes in Mauritius.

The pattern of dengue cases was highly fluctuating from one year to another with the coefficient of variation being 87.3%. This high variability implies that other factors than long term climate changes, for instance, appearance of new dengue virus serotypes or alterations in population susceptibility, are important determinants of outbreak patterns. Outbreaks of high incidence were reported in 2009 at a rate of 8.7 cases per 100,000 population, 2015 at 12.4 per 100,000, and 2019 at 18.9 per 100,000, all of which were linked to the introduction or re-emergence of particular DENV serotypes. This pattern emphasises the role of viral serotype change as the key determinant of outbreak size, notwithstanding climatic variation.

Spatial Dynamics of Dengue

Mapping of the study area showed that the hotspots of dengue fever in Mauritius varied over the period of study. The mean centre of dengue shifted 12.3 km ± 1.8 km inland over the study period ($p < 0.001$). This change in the distribution of dengue cases towards the interior could be explained by a number of factors such as, changes in climatic conditions favourable for the breeding of the vectors, trend in the expansion of urban areas, and population displacement.

In addition, the study established that there was the spatial aggregation of dengue cases as time went on. The global Moran's I statistic for spatial autocorrelation of dengue incidence moved from 0.18 in 2000-2005 to 0.42 in 2018-2023 ($p < 0.001$). This elevated spatial autocorrelation implies that the distribution of dengue cases is becoming more clustered, which could be due to the appearance of new, long-lasting transmission 'hotspots' or the convergence of environmental and social risk factors.

Climate-Dengue Relationships

The analysis revealed a number of time-lagged relationships between climate and dengue incidence which may help explain the pathways through which climate change affects disease risk. Cross-correlation functions revealed significant positive correlations between mean temperature and dengue cases at multiple time lags: 8-10 weeks ($r = 0.63$, $p < 0.001$), 16-18 weeks ($r = 0.47$, $p < 0.001$), and 24-26 weeks ($r = 0.39$, $p < 0.01$). Such lags may be an indication of the temperature influencing the different life stages of a mosquito, the replication of the virus within the vector and the interaction of people with the vector.

The use of DLNM established a minimum morbidity temperature (MMT) of 24. 7°C (95% CI: 23.9-25.5°C). This finding implies that, although temperature is often associated with dengue risk, it is not monotonic. It is possible that there are thresholds of temperature that lead to the highest transmission rates and beyond which the vectors cannot survive or people are less likely to venture outdoors and thus the disease risk is altered.

Vector Ecology

The analysis of the entomological surveillance data revealed that Aedes albopictus population dynamics were temporal and spatial in Mauritius, the country with the primary dengue vector. The overall average Breteau Index (BI) of the island, which is an indicator of container breeding mosquito population, also rose from 15.3 (95% CI: 13.8-16.9) in 2005 to 28.7 (95% CI: 26.9-30.6) in 2023, representing an 87.6% increase. This increase in the population of vectors correlates with the upsurge in dengue cases and might indicate that climate change may be contributing to this by encouraging the breeding of the mosquitoes.

The patterns of vector risk also shifted in space. The area of the island that is considered to be at a"high risk" (BI >20) was 23.7% in 2005 it increased to 41.2% in 2023. This increase in the high risk areas shows that the conditions for breeding of Ae. The species aedes albopictus are gradually spreading all over Mauritius, which may be attributed to factors such as climate changes, increased urbanization and human activities that favour the breeding of the vector.

Vector Competence

Vector competence studies of Ae. Under experimental conditions, Ae. albopictus populations were shown to have temperature-dependent DENV infection, thus explaining the link between climate change and dengue transmission. Mosquitoes incubated at 28°C showed significantly higher infection rates (72.3% vs. 45.7%, $p < 0.001$) and dissemination rates (58.9% vs. 31.2%, $p < 0.001$) compared to those at 22°C. These outcomes indicate that, due to global warming, the conditions may become favorable for the vector to become infected and spread the virus with possible higher dengue risk.

Also, the extrinsic incubation period (EIP); the time that the virus takes to multiply and become detectable in the mosquito's salivary glands also reduced from 12.3 ± 1.1 days at a temperature range of 22°C to 7.8 ± 0.9 days at 28°C as compared to the control ($p < 0.001$). This temperature related reduction in the EIP could greatly enhance the transmission rate of the virus as the virus can be transmitted at faster rates as soon as the temperature rises.

Socio-ecological Factors

Several socio-ecological determinants of dengue risk were also established through multivariate logistic regression analysis. Population density was found to be an important determinant, with a 10% rise associated with a 1.23-fold increase in dengue incidence (95% CI: 1.18-1.29, $p < 0.001$). This relationship may be attributed to higher opportunities for humans to come into contact with the vector especially in overcrowded areas as well as the availability of artificial containers for breeding of the vector in the urban setting.

Socio-economic status also emerged as an important factor in the construction of dengue vulnerability. The enumeration areas in the lowest quintile of socio-economic status as determined by the incomes of the households had a 2.17 times higher incidence rate (95% CI: 1.89-2.48, $p < 0.001$) than among the subjects with the highest quintile of energy intake. Such variation in the dengue risk by socio-economic status reveals the social determinants of health in climate change related diseases and underlines the significance of interventions in the marginalised population.

Water Management and Land Use

Water management practices, land use and dengue fever were also closely related in the study. Counties where more than half of the households stored water regularly had a 1.76 times higher Breteau Index (95% CI: 1.58-1.96, $p < 0.001$) than the areas with less than 10% household water storage. This result shows the significance of the water storage in the production of breeding places for mosquitoes, especially in relation to the fluctuation of rainfall and water scarcity problems.

Land use change, especially the process of urbanization was also found to be a key determinant of dengue risk. A 10% increase in the area of land classified as urban in an enumeration area was linked to a 1. 32-fold increase in dengue incidence (95% CI: 1.24-1.41, $p < 0.001$). This relationship could be attributed to higher human population density, alteration of microclimate within the region (for instance the heat island effect) and the provision of artificial structures that harbor the species within the towns.

Human Mobility

Using mobile phone data on human movement, with anonymity preserved, the authors identified key determinants of spatial dengue transmission. The enumeration areas identified with high incoming flow from the dengue hotspots had 1.89 times higher incidence rates (95% CI: 1.72-2.08, $p < 0.001$) times higher than in areas with low incoming flow. This is a clear implication of human movement in the transmission of dengue virus across the island and a clear indication that human movement must be factored into the strategies that are being used in the fight against the disease.

Intervention Effectiveness

The study aimed at comparing the effectiveness of different public health interventions thus showing the level of success. Community-based vector control campaigns of the larger scale were linked with a 34.7% reduction (95% CI: 28.9-40.1%, $p < 0.001$) in dengue incidence over the subsequent 8 weeks. Although notable, this moderate effect implies that there could be the inability of conventional vector control measures to contain dengue transmission in view of enhanced climatic suitability for the disease.

A pilot study in a high-risk area with Wolbachia-infected mosquitoes produced better results; 67.8% reduction (95% CI: 59.4-74.9%, $p < 0.001$) in dengue incidence was observed in the two years after release in comparison to the control areas. This study implies that, in the light of climate change, new ways of controlling vectors may provide more efficacious tools for reducing the dengue risk.

Future Projections

Climate change scenarios for the island of Mauritius predict a range of changes in the coming middle of the century, which is relevant to the further development of dengue fever. Under the SSP2-4. In the 5th scenario, mean annual temperature was expected to rise by 1.8°C (95% CI: 1.4-2.2°C) by 2050. This significant rise in temperature will also be likely to increase the climatic suitability for dengue transmission across the island even more.

The study predicts that the 'high risk' area of Mauritius for dengue fever will rise from 32.7% to 57.4% (95% CI: 51.2-63.8%) by 2050. Such an increase in the high-risk areas shows that it is high time to develop preventive measures to tackle the increasing menace of dengue in the climate change.

Economic Impact

The economic assessment of the impact of dengue has put the annual economic costs to Mauritius at approximately 0.3% of GDP with a possibility of rising in the future. At present, it stands at 3% of GDP, but under the prevailing weather condition, it should be 0.8-1.2% of GDP by 2050. This paper also uses the 5th scenario, with no consideration for adaptation. This estimated increase in economic burden shows the possible macroeconomic consequences of the climate change in dengue transmission risk and underlines the necessity to allocate resources to the climate change adaptation and dengue prevention measures.

6.2 LIMITATIONS OF THE STUDY: AN IN-DEPTH ANALYSIS

Data Resolution and Microclimatic Variations

Despite employing high-resolution climate data and using climate data with 1 km grid size, basic microclimatic properties in the complex terrain of Mauritius may not have been adequately considered. There was localized clustering of temperature at scales below 500 meters to higher elevations in the central highlands and lower elevations in the coastal urban areas. Moran's index of spatial autocorrelation was (Moran's I = 0.73, $p < 0.001$).

For example, in Port Louis fluctuation in temperature ranges from 2.8°C (95% CI: 2.3-3.3°C)are the changes of mean temperature between adjacent grid cell during the period of the high urban heat island intensity. These could be some of the tiny climatic differences that would influence the vector-borne disease transmission and ecology at the local scale. A sensitivity analysis revealed that extension of the model to include higher resolution temperature data in a sample set of high risk areas improved model fit by 12.3% (adjusted R^2 increase from 0.684 to 0.768), indicating that the main analysis might have underestimated the role of local climate variation.

Temporal Scope and Long-term Climate Variability

The dataset used here comprises of dengue data from the year 2000 to 2023, however the latter part of the series may not be sufficient for accurately understanding long run climate – dengue nexus. Analyzing the climate time series of mean annual temperatures and annual precipitation (1950−2023), this study identified notable multi−decadal fluctuations in both temperature and precipitation that are beyond the study period with temperature fluctuations having the dominant period of 23.7 years, and the amplitude of 0.4°C and the dominant period of precipitation oscillation is 18.9 years and an amplitude of 178 mm.

Such long-term cycles might alter the climate-dengue associations that are described above. For instance, comparing SA with dengue transmission rates it was established that while high coherence existed at periods of 2–7 years and 15–20 years ($r = 0.58$, $p < 0.01$, $r = 0.47$, $p < 0.05$ respectively), this study period might not be sufficient in capturing the effects of larger climate systems on dengue epidemiology

Vector Species Dynamics

Although the study was conducted and justified based on the current ecological context where Aedes albopictus is now predominant in Mauritius accounting for 97.3% of collected Aedes mosquitoes, n = 15,623, the study might be under-representing the future potential of Ae. aegypti . The modelling based on Climate envelope theory suggests that by 2050, under the RCP 8.5 scenario there was a significant reduction in the climatically suitable area for Ae. As for the share of aegypti in Mauritius, it could rise by 28.7% (95% CI: 22.1-35.3%).

The studies embarked on comparing vector competence in the laboratory resulting in the observation that local Ae. His aegypti populations had a 1. 4 times higher (95% CI: 1.2-1.6), vectorial capacity for DENV-2 to Ae. albopictus at 28°C. This disparity rose to 1. 7 times (95% CI: Intrinsic development rates were determined to occur at 32°C (95% CI: 1.5-1.9) and future warming appears to scale up the development rate of Ae. aegypti's role in transmission.

Economic Modeling Limitations

To predict the economic effects various forecasts have been drawn up based on the so-called static computable general equilibrium (CGE) model, which does not allow for dynamic feedbacks between health impacts and adaptations on the one hand, and economic growth on the other. One way sensitivity analysis showed that the model was robust to changes in individual parameters (for example disability weights, indirect costs) the estimated economic burden ranged from 0 6% to 1.8% of GDP by the year 2050.

One particular limitation is that the proposed model is not capable of giving particular consideration to non-linear effects of economic activity. Historical data from severe outbreak years (2009, 2015, 2019) suggest that when dengue incidence exceeds a threshold of approximately 15 cases per 100,000, indirect economic costs (e. g. , tourism revenue loss) increase exponentially rather than linearly (β = 1.76, 95% CI: 1.58-1.94).

Generalizability to Other SIDS

Hence the generalization of the finding of this study to other SIDS is somewhat constrained due to peculiarities of Mauritius. Comparing the temperature-dengue figure with that of four other SIDS (Seychelles, Maldives, Fiji and Barbados), the researchers found the relationship varied enormously. For instance, the temperature-dengue association in Mauritius (relative risk [RR] = 1.27 per 1°C increase, 95% CI: 1.18-1.36) differed significantly from that in Barbados (RR = 1.12, 95% CI: 1.05-1.19) and Fiji (RR = 1.38, 95% CI: 1.29-1.47).

Socio-economic factors also differed significantly for the proportion of households without access to improved water sources which ranged 0.3 %, in Mauritius up to 12.7% in Fiji, which may affect peoples' water storage and vector breeding places.

Intervention Analysis and Causal Inference

As it will be see, the observational nature of the intervention data precludes causal inferences. For instance, the estimated 34.7% reduction in dengue incidence following community-based vector control campaigns had a wide confidence interval ((95% CI: 28.9-40.1%), hence the effect of latent variables may have contributed to the findings.

Using difference in differences comparing treatment and comparison locations, the author noted that as much as 22.3% (95% CI: 18.7-25.9%) of the observed effect could be explained by coinciding temporal fluctuations in climate conditions and changes in the population's immunity. Uncertainty in efficacy estimates is due to the absence of randomized controlled trials, and when available, have limited sample sizes for interventions as Wolbachiainfected mosquito releases.

Model Assumptions and Non-linear Dynamics

The climate-dengue models that have been created within this research presume constancy of these relations in the future climate conditions. Generalised additive models (GAMs) dictated non-linear increase of dengue risk with thresholds at mean temperature of 29.3°C (95% CI: 28.9-29.7°C) and total monthly rainfall exceeds 300mm (95% CI: 285-315mm).

Crossing these thresholds was possible only in 7.2% of the observed month-location combinations, but such events are expected to happen in 18.7% (95% CI: 15.9-21.5%) of cases by 2050 under RCP 8.5. The potential for such non-linear responses considerably complicates long-term analysis with large degrees of uncertainty.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH: A COMPREHENSIVE ROADMAP

1. Enhanced Climate Monitoring Network

The current climate monitoring system in Mauritius though offers important data does not offer the adequate spatial resolution to characterise microclimates which are key in determination of disease transmission rates of dengue. To overcome this weakness, the actualization of a high density of AWS networks in the island is recommended.

More particularly it should aim at reaching one weather station every 10 km² as against one station per 50 km² at present. Indeed if this is achieved, then it will be five times better to detect small scale climate patterns in a given region for instance due to more complex topographical features such as in the central highlands.

More priority should be given to location new stations in microclimatic areas but primarily on central highlands because from experience temperature lapse rates range from 4.8°C/km to 7.2°C/km. Such positioning will assist in recording a broad spectrum of climatological conditions in the island’s geographical landscape.

In urban regions, the existing network should be backed with specific UHI measurement. It can be done by comparing conventional station data collected in urban areas, transects consisting of sensors mounted on vehicles, and incorporating LST data obtained from satellites. Such a sequential approach will facilitate the development of fine scale urban climate maps necessary for explaining dengue distribution in congested neighbourhoods.

The improved climate monitoring should also correlate with the number of additional sensors addressing soil moisture as well as evapotranspiration. These parameters are important in determining local water balance which is important in the availability of mosquito breeding sites. Information from this expanded network should be relayed to a master database in real-time, to make the data freely available to anyone who needs it; researchers or public health practitioners. The Data Accuracy Risk Control will require the use of Quality Control Algorisms and Routine Calibration of the Strong Algorithm to ensure the database is accurate.

With this improved climate data collection, it is possible to have a better dengue risk assessment of areas with complex topography by a margin of 15-20%. It could also greatly provide a better prediction about the scenario and consequently improve the alert systems and directed approach of interference.

2. Advanced Vector Surveillance Systems

Existing vector surveillance strategies in Mauritius, although informative, are generally low in temporal and spatial resolution to allow for quick switching and adaptation depending on changes in vector species. To overcome this shortcoming, therefore, we recommend the establishment and implementation of a network of smart mosquito traps in the island of Sri Lanka.

These smart traps should have the functionality of recognizing the species of the caught mosquitoes in real-time mode. This would allow for immediate distinction between Aedes albopictus, the current dominant vector and Ae. aegypti which increases in incidences with change of climate.

The traps should also be able to transmit data on the species of the captured mosquito, the number of caught mosquitoes as well as potentially arbovirus presence (through integrated swift testing methods) to a database. Such a live feed would enable the identification of anamorphic behavior in vectors or the emergence of new vector species.

The target density laid out for smart traps in the threat regions should be one smart trap per each 5 km² of land area while threat zones should be estimated using the historical data of hot spot occurrences and modeling. This density would offer a high spatial resolution now lacking in vector data so that interventions could be carried out at this scale.

For the smart trap network, the standard eDNA sampling of important water bodies should be conducted regularly. This technique would give an early indication of the vectors in acts of 'egging' or 'ovipositing' in the potential breeding sites before mosquitoes in the adult stage are caught in the traps.

The data of smart traps and eDNA sampling should be stored and analyzed in a one, centrally located machine-supported early warning system. This system would use both vector data and climate/human case data to forecast density of vectors with a lead time of two to four weeks. Such early signs of change in the vector population and its imminent spike could be easily contained by the highly localized strategies this superior kind of surveillance system permits. Small-scale trials show such highly focused control measures could potentially cut down transmission in targeted locales by between 50 and 60 per cent.

Furthermore, this system would offer invaluable data for the research that would lead to more complex modeling of how the population of vectors responds to the changing climate conditions. This could importantly improve knowledge on how climate change could affect future patterns of disease transmission.

3. Longitudinal Population Immunity Studies

The ability to monitor the current and evolving trends of population immunity in Mauritius has been handicapped in the past by a certain absence of systematic and long-term data collection on serological trends. In order to fill such an important gap in knowledge, we suggest the conduct of a longitudinal cohort study with hundreds of subjects followed in multiple centres.

The target of the cohort should be around 5,000 people and it is necessary to choose respondents everywhere in Mauritius. Strata include age, location including urban and rural areas, and micro climatic regions and socio economic status of the population.

All members of the cohort should undergo serological tests twice a year in order to determine the shifts in immunity to all the four DENV serotypes present. These surveys should use technologies that can distinguish between the different serotypes as well as between the recent and the past infections. This will make it possible to distinguish new cases of DENV disease, including cases of subclinical infection, which will give a more accurate idea of the occurrence of the disease. Besides serological information, the study must also include other participant activities, mobility, and health-seeking behavior information. This can be done also by the consistent application of surveys and in as much as possible through the use of GPS in the developed Mobile Applications.

It should also incorporate high-resolution mobility data from ‘hashed’ mobile phone records (as used in this study) with relevant privacy precautions to simulate human movement at the population density level. This will enable modeling of how human movement affects spatial dengue heterogeneities.

Information on climate and vector density and distribution should be obtained at the respective places identified for the study so as to identify the relationship between population immunity and disease transmission.

Also, due to the planned duration of the investigation, which should be at least 10 years with an option to continue, it will be possible to detect long-term dynamics of population immunity. This is important in order to determine aspects like climate conditions and viral variants of the immune system overtime.

As it is capable of offering a detailed overview of temporal and spatial shifts in population immunity this work may increase the reliability of forecasts by as much as by 30%-40%. These improvements in prediction might greatly contribute to the effectiveness and the timing of public health interventions, which would prevent a great number of situations from occurring.

It provides a rich dataset for further construction and testing of the more advanced mathematical models on the dengue transmission. These will be important for predicting future dengue risk at places under different climate change scenarios and for assessing the impacts of different interventions.

4. Multi-Pathogen Arboviral Surveillance

The recent emphasis on dengue virus in Mauritius while relevant maybe masking other arbovirus risks in the country. To build a better picture of the arboviral makeup of Canada and the possibility for change under climate change, it should be noted that the surveillance should not be limited to WNV but should include chikungunya and Zika.

A priority measure should be the use of multiplexed PCR testing of all patients with clinical manifestations of dengue. The aim should be to confirm at least 80% of all the fevers reported for these multiple arboviruses simultaneously. The approach will also be more helpful to the patients as well as give a clear description of which arboviruses are in circulation within the population at any one time.

Besides increasing the number of diagnostic tests, we propose the regular phylogenetic sequencing of a portion of those samples that are positive. It is proposed that this should be attempted with about 10% of positive cases of all the arboviruses that have been detected. These shall enable tracking of the patterns of evolution of the virus over period as well as detection of new strains or genotypes introducing themselves into Mauritius.

The phylogenetic data will be most useful in studying the trend of viral importation and/or transmission at that or another level. After matching viral sequences with global databases, the researchers are able to reconstruct the probable pathways of viral entries to Mauritius and viral dynamics following an entry.

In addition to human case surveillance we propose arbovirus surveillance in vector species and other vertebrate hosts. This can be done by testing mosquito pools drawn from the smart trap network put forward in Section 2 periodically. The use of mosquitoes in collection of samples will always give information on arbovirus activity before human infections have emerged, thus helpful in early warning systems.

The multi-pathogen surveillance program should also have One Health that would look at the presence of arboviruses in animals that may act as their hosts. Dengue mainly affects people but other arboviruses can eye birds and rodents. Further study of other domestic animals, livestock, and wildlife inhabitants especially primates and birds can be done through routine sampling and testing in an attempt to understand the overall arbovirus circulation in Mauritius.

Information generated from the enhanced surveillance should be collected into a single database to support the real time monitoring and mapping of arboviruses. Ideally, this system should be programmed to send warning signals when it recognizes that it is dealing with a new virus, or that the number of viral cases is suddenly high.

The expanded surveillance program could detect additional virus-virus interactions, and thereby elucidate phenomena that increased or decreased arboviral transmission by as much as 10-25%, that were not previously known or recognized. Such information will turn out to be important in predicting where and how climate change might impact the broad picture of arboviral diseases in Mauritius, including but not limited to dengue.

Furthermore, the early detection of this system could extend the speed to threats of arboviruses that have not been identified previously. Together with the other recommendations in this paper, this may help to build a more resilient and adaptable public health response to climate-sensitive vector-borne diseases.

5. Comparative SIDS Climate-Health Observatory

Despite the concentration on Mauritius the implication of the findings for other SIDS is somewhat restricted. To this end, we suggest the formation of a Comparative SIDS Climate-Health Observatory that will connect Mauritius to a network of at least five SIDS across the various oceans.

Islanding of the observatory should accommodate a variety of islands, if not Caribbean (e. g. Barbados), the Pacific (e. g. Fiji) or other Indian Ocean (e. g. Seychelles, Maldives). Such a geographical distribution will enable direct cross-sectional study across the various climate zones and the broad socio-economic levels that are known to influence the occurrence of the diseases. It became clear that one of the main focuses for the observatory should be the existing procedure of data collection and its unification of the islands. This should include climate data where the distances between the weather stations are the same and the measurement procedures are standardized, methods of vector surveillance, and case definitions for arboviral diseases, and socio-economic status indicators.

The observatory should establish a common data space and work on the use of common platforms for the simultaneous and comparative analysis of data across the network. The following platform should be developed with the feature of data security and protection of the health information while encouraging collaborative research.

There should be organized meetings at least once a year with the presentation of the data collected during the last 12 months and with participants from all the islands involved in the research. It seems that these workshops could have been held in turn in the different islands so as to enhance the mutual work and comprehension of the specific contexts.
The observatory should also build its own research capacity with special emphasis on the Island areas lacking enough research capacity. This could envisage training, staff mobility, and use of superior analytical tools and knowledge, for example.

A core research agenda for the observatory should include:

1. Comparison of the climate-dengue links in various island settings
2. Assessment of the appropriateness of diverse adjustment measures in diverse geographic locales of the SIDS
3. Study of the extent to which other factors (geographical, infrastructural, cultural and otherwise) influence the effect of climate change on the transmission of dengue virus.
4. Climate-health models focusing on SIDS and starting from the specific social, economic and geographic characteristics of the islands, including both vulnerability and resilience factors.

In this way, the observatory would be able to draw comparative conclusions concerning how the successful adaptive capacity of a particular country might be up to 20-30% more efficient than if purely local solutions were sought. This approach may significantly improve the approach to climate health intervention in different island settings, which would be instrumental to other SIDS all over the world.

Additionally, the observatory can and should provide a strong base for promoting SIDS' issues at the climate-change / health connectivity level with the global entities to guarantee that the voice of Island nations is properly considered in the processes of building the adequate international policies.

6. Urban Microclimate and Dengue Risk Modeling

Given the high population density and climatic conditions in urban areas of Mauritius there is need to undertake more focused research on microclimate impact on dengue risk in these areas. It is therefore important that high resolution urban climate models of major cities in Mauritius are established with emphasis on Port Louis the capital and largest city in Mauritius.

These models should be completed at a scale of 10 metres or better so that heat, moisture, and winds at street level can be accounted for. The models should integrate various urban features including:

1. Building morphology: The design of the building, the height, how close the building is to one another and the amount of floors present.
2. Green space distribution: Parks, streets, and other individual gardens
3. Surface materials: Reflectance and thermal characteristics of various components of a city
4. Anthropogenic heat emissions: From the traffic, the conditioner, and the industries
5. Water bodies: Artificial such as fountains and natural like river frontage, coastlines etc, and built-ins such as swimming pools and the like.

The urban climate models should be connected with the regional climate models in a dynamical way allowing to take into account the large-scale circulation and climate change scenarios. This will enable one to model future warm climate changes whereby cities will be exposed to particular global warming pathways.

To link these urban climate models to dengue risk they ought to be integrated with human mobility and vector ecology agent based models. These integrated models would simulate:

1. Everyday mobility of humans in the city landscape
2. Microclimate conditions influencing the breeding, survival and dispersion of mosquitoes
3. Contact index and probable instances of pathogen transmission through human-vector contacts

They should be calibrated and validated using data from the enhanced climate monitoring network explained in section 1 and the advanced vector surveillance system explained in section 2. Furthermore, quite high-resolution satellite imagery and, especially, LiDAR data should be employed in order not to distort the representation of the urban environment.

After the formulation of these models they are used to perform scenario simulations to examine the effect of various urban planning strategies on the creation of UHIs and the risk of dengue fever. Potential interventions to model could include:

1. The idea is to increase the coverage of green areas in the areas of urbanization by 20 percent.
2. Applying cool roofs on 50 percent of the buildings
3. Invest in modifications of the orientations of the streets that cause polluted air to flow out of them.
4. Adjusting practices that control water at the basin fact to moderate water accumulation

All the situations should be looked at with regard to possible effects on temperature in towns, number of breeding places for vectors, and consequently, dengue mosquitoes, and the likelihood of dengue fever occurrence.

The urban microclimate-dengue models developed in this dissertation could help elaborate on urban planning measures that might decrease the intensity of the UHI by 1-2 °C. This in turn could bring about a reduction of dengue infection risk in the urban area by 15-25% through changing the conditions unfavourable to the vector and the virus.

Moreover, The above models may help in designing specific launch intervention strategies by locale, which can help the public health officials tailor available resources to the high-risk urban locales when such periods are anticipated.

7. Adaptive Intervention Strategies and Decision Support Systems

Since the transmission of dengue is volatile especially with regard to climate factors, then a much more contextual and adaptive approach is required. As the basis for the development of the detailed plan, it is suggested to create a complex decision support system that would be able to suggest and assess the effectiveness of the related adaptive intervention policies in the process of their implementation.

The core of this system should be a machine learning algorithm that integrates multiple data streams, including:

1. Climate data in real-time from the improved and expanded monitoring system
2. Sampling information gotten from smart trap network on vector surveillance
3. Case data from multi-pathogen surveillance system in humans
4. Seroprevalence data from the interviewed population of the described longitudinal cohort study
5. Global human movement data from mobile phone records in the form of anonymous call detail records
6. Socio-economic and demographic data

This should be a trained algorithm based on the past occurrence in order to be in a position to establish a relationship between such factors as and the risk of transmitting the disease. Consequently, the algorithm of the system should also adjust its analysis to fit the fresh data arriving in the course of time.

The decision support system should be capable of recommending a suite of adaptive interventions, including:

- Dynamic vector control strategies: Using data collected in real-time entomological indices and climate conditions in order to modify the scheduling, administration and intensity of vector control programs.

- Targeted community engagement campaigns: Initiating vigorous public sensitisation as well as pest eradication activities on the forecasted endangered zones.
- Temporary modification of urban environments: Suggesting short-term actions like: the use of large objects when there are obvious changes inclimate or situation of heavy rain or covering big water bodies or increasing trash pick up.
- Healthcare resource allocation: Helping in the determination of where to transport medical stock and manpower in accordance to estimated spread of the disease.

In the light of these adaptive practices, we suggest that further study of its efficiency should be done through a large scale, randomized controlled trial. This cocktail trial should include at least 20 high risk communities where the above subjects reside and randomly selected into the adaptive intervention approach or the traditional static intervention. The trial should last at least three transmission seasons to take into account year to year variation.

In the course of trial, relevant data should be gathered on the general application of the interventions, costs incurred, perception by the community and above all the occurrence of dengue fever. This database will enable a proper assessment of the adaptive approach in comparison to the normal techniques.

The decision support system should also have an interface by which the public health can view the current risk patterns, the recommended interventions and inputing on the implemented interventions. The user-friendly, buttery and flexible interface particularly for field use should be made available in both the desktop and the mobile gadgets.

Overall, dengue’s incidence could be decreased by 30%-50% through higher-value interventions if the measures would be implemented within this adaptive system, compared to standard fixed strategies. However, it could also imply better utilization of resources, since interventions would only be delivered at the peak risk points.

It means that the information, which was provided by this system, could be used not only for short-time decision-making but also for the formation of long-term strategies and policies, providing the efficient control of dengue in conditions of constant climate change.

8. Integrated Economic and Health System Modeling

The following issues of dengue and climate changes are still hard to grasp: the economic effects for changing climate conditions and the ability of the health system to cope with them. This is the knowledge gap that we suggest that development of an integrated economic and health system model will be able to fill.

The model must be a system dynamics model because the problem involves feedback between climate change, transmission rate of dengue fever, effects on the economy and situation of the health system. Key components of the model should include:

1. Climate Module: Including extensions of temperature and precipitation anomalies and variability with different climate change scenarios.
2. Dengue Transmission Module: On the behaviour of climate conditions, vector density and population immunity, estimating the incidence of dengue fever.
3. Economic Impact Module: Calculating direct and indirect costs of dengue, including healthcare costs, productivity losses, and impacts on key sectors such as tourism
4. Health System Module: Simulating the readiness of future healthcare facilities, number of beds, supplies and staff in anticipation of dengue epidemics.
5. Adaptation Measures Module: Modeling the effectiveness of the actual policies meant for adaptation including vector control, early warning, and health system investment.

The model should include adaptive behaviours at the individual and policy levels. This could entail alterations in water storage and Conservations, treatment seeking behaviour and even policy measures during or due to epidemic or in response to long term climate shifts.

When it comes to evaluating the model's stability, we suggest that the authors should perform numerous sensitivity analyses; changing the values of significant parameters to determine the impact they produce. Whenever probabilistic projections have to be made, the Monte Carlo simulation should be used in order to obtain a set of possible future values rather than a single point estimate.

In addition, the variables that have been incorporated in the model should be calibrated based on historical data on Mauritius occasioned by dengue incidence, other economic indicators, and performance of the health system. It should also be tested against data that were not used in the calibration process to determine the measure's predictive validity.

After the development of the model it has to be employed for the number of policy simulations that would give the long term effects of the distinct adaptation measures under distinct climate change scenarios. These experiments could include:

1. Discounted cost comparison of various vector control methods and their impact on population during a period of 50 years.
2. Evaluating the prospects of early warning systems and rapid response automated investment opportunities to avoid huge losses.
3. Assessing the dengue health system needs, under worst-case climate conditions from a long-term perspective.
4. Identifying possible breakpoints at which the economic burden of dengue is likely to rise as a result of climate change making its mitigation measures nearly impossible or affecting a major segment of the economy.

This model may cut the uncertainty ranges in economic projections by 25–40%, assisting in giving more complete projections of dengue burden and its economic consequences. It might be particularly valuable for the long-term prognoses and resource allocation, which can deepen policymakers' understanding of the climate change adaptation measures to be taken.

Furthermore, the model might be useful in advocacy as a way to show what will happen if the climate change issue is not addressed, and what advantages may be obtained from early preparedness.

9. Participatory Research and Community Engagement

Dengue control and climate survival cannot be achieved without the public of the community. The improvement of local adaptive ability is another crucial issue, and we believe that a wide-spread participatory research and community engagement program should be used to develop culturally suitable and sustainable solutions.

It should contain a citizen science component that will involve at least 5% of the country's population in dengue risk assessment and mitigation. This could be facilitated through the development of a user-friendly mobile app that allows citizens to:This could be facilitated through the development of a user-friendly mobile app that allows citizens to:

1. Inform residents of their neighbourhood on the possibility of breeding grounds being present in those areas.
2. Record use of anti mosquito protective systems and devices used at the intended targets.
3. People should report suspected dengue symptoms (while taking measures to ensure that they do not reveal their identity).
4. Get the latest, real-time risk notifications as well as prevention tips for the area where you live.

To increase engagement over the very long-term, the app should have 'use it or lose it' aspects such as community goals for destroying breeding sites or individual achievements for using covers every day.

Apart from the app, the program means to foster a network of community climate-health change advocates. Some of these volunteers should be trained in basic entomology, climate science and some aspects of public health. They would act as intermediate between researchers and their communities to spread information and to demand action.

It should also aim at incorporating traditional knowledge systems especially from the coastal and rural areas into risk analysis of climate and health factors and into the development of response strategies. This could involve:

1. Entering into extended face-to-face interviews and focus group discussions with the elders in the community to capture those traditional ways of predicting weather and vector control.
2. Encouraging the holding of knowledge-sharing workshops in which scientific research conclusions are discussed with traditional knowledge systems.
3. The integration of conventional knowledge with western knowledge in developing locally specific adaptable measures that are scientific from the regional ecological requirements.

For reasons of visibility and applicability of the findings, we suggest the formation of climate-health action committees in each district in Mauritius. It was seen that these committees should comprise the elements from public health, local government, the community and the citizen science program. They would be responsible for:

1. Consulting sources of climate data and literature, as well as , publications about possible health effects.
2. To provide community specific adaptation strategies and measures.
3. Managing community mobilisation during increased risk periods.
4. Giving considerations to the researchers about the real life difficulties in implementing the interventions.

The program should also have a highly educational profile, cooperate with schools and prepare climate-health-related seminars and frequently hold community meetings and events.

Through development of such a level of community participation, the program had the potential to increase the acceptance of an intervention by 25-35% and decrease response time to 40-60% in local threats of dengue. Further, it would produce a substantial amount of qualitative data that could be used to tailor intervention strategies to the local context by identifying peoples' attitudes, actions, or coping mechanisms that scholarly articles seldom capture.

Such a participative approach will not only increase the adaptive capacity of a community but will also help in the process of demystification of scientific knowledge as the cultural and natural adaptive capacities of the community would come to the forefront to forecast and counteract these health effects of climate change.

10. Transdisciplinary Research Hub

The links between climate change and dengue are many and diverse, thus requiring participation of scholars from various disciplines. Such require the establishment of a Climate-Health Resilience Research Hub with institutional home that will offer a common ground for intense interdisciplinary and intersectoral engagement.

The hub should bring together experts from a wide range of fields, including but not limited to:

1. Climate science
2. Epidemiology
3. Entomology
4. Public health
5. Urban planning
6. Economics
7. Social sciences
8. Data science and AI
9. Environmental engineering
10. Health systems research

The physical environment or layout of the hub physical plant should be capable of supporting interoperability, among them shared open work areas, fully equipped laboratories and sophisticated computational facilities for conducting climate and diseases related simulations. Since the impacts of climate change in SIDS are diverse and interconnected across multiple sectors it is imperative that the focus of the hub is on developing integrated assessment models. Such models should conceptualize the findings to integrate ideas drawn from all the research streams described in the previous recommendations.

The hub should be formulated in the principle of ‘team science’ whereby research protocols and databases should be harmonized. This could include:

1. Organization of cross-disciplinary seminars and workshops to present the results and methods of investigation.
2. Organizational rotations in which researchers temporarily transfer to other teams not their own field of specialty.
3. Multiprofessional field missions to enable interdisciplinary research on the links between climate change and health on the scene.

Since research should not be done for the sake of doing it but for it to be utilised in practice, then it is good that the hub came up with a knowledge translation unit. This unit would be responsible for:

1. Writing of policy briefs and policy recommendations emanating from the research conducted.
2. Of conducting frequent stakeholders’ meetings with the policymakers, the health care practitioners, and other community members.
3. Extending awareness raising and education outreach aiming at officials in the public health sector and other healthcare practitioners pertinent to climate-health resilience training.

It should also function as a regional ‘knowledge exchange hub’ building the capacity of the other SIDS’ researchers and practitioners through training and twinning. This could assist in developing a network of climate-health specialists within the Indian Ocean IOM, and other global regions.

To support the proposed hub funding should be sought from the national government, international climate finance and research grants for international climate finance. One of the lessons that can be drawn here is that a dispersed funding model will be essential for building the sustainability of the initiative in the long term.

It is for this reason that this level of cross cutting collaboration if supported at the hub can lead to the generation of new knowledge and creativity to counteract adversities by the generation of amazing adaptive measures. These strategies could potentially lower climate change associated public health threats by 30-50% to current best practices.

In addition, the proposed hub would act as a best practice for multi-disciplinary climate-health research that could well prompt same-neighbor-type scenarios in other similar environmentally and healthly affected areas.

Consequently, these ten identified research suggestions are integrated and could serve as a straightforward roadmap to investigate the impacts of climate change on dengue fever transmittances in Mauritius. This research agenda could actively contribute to the improvement of the climate resilience of the health system in Mauritius and offer lessons learned to other SIDS that face similar challenges explained by pertinent knowledge gaps and ICT developments.

APPENDIX

1. SUMMARY STATISTICS OF DENGUE CASES

Statistic	Value
Total Cases (2000-2023)	3,465 cases
Mean Age of Patients	31.5 years
Median Age of Patients	30.1 years
Sex Distribution	Male: 52%, Female: 48%
Percentage of Severe Cases	12%
Mortality Rate	0.5%
Average Duration of Symptoms	7.5 days

2. CLIMATE VARIABLE SUMMARY

Climate Variable	Mean	Median	Standard Deviation	Range
Temperature (°C)	25.6°C	25.4°C	2.1°C	22.5°C - 30.7°C
Rainfall (mm)	180 mm	165 mm	45 mm	90 mm - 300 mm
Humidity (%)	78%	77%	5%	65% - 90%
Wind Speed (km/h)	12 km/h	11 km/h	3 km/h	6 km/h - 18 km/h
Sunlight Hours	7 hours	6.8 hours	1.5 hours	4.5 hours - 9.3 hours

3. CORRELATION MATRIX BETWEEN CLIMATE VARIABLES AND DENGUE INCIDENCE

Variable	Temperature	Rainfall	Humidity	Wind Speed	Sunlight Hours
Dengue Incidence	0.65	0.72	0.58	-0.31	-0.45
Temperature	1.00	0.59	0.40	-0.22	-0.34
Rainfall	0.59	1.00	0.55	-0.20	-0.30
Humidity	0.40	0.55	1.00	-0.25	-0.28
Wind Speed	-0.22	-0.20	-0.25	1.00	0.15
Sunlight Hours	-0.34	-0.30	-0.28	0.15	1.00

4. TIME LAG EFFECTS BETWEEN CLIMATE VARIABLES AND DENGUE INCIDENCE

Time Lag	Temperature	Rainfall	Humidity	Wind Speed	Sunlight Hours
No Lag	0.65	0.72	0.58	-0.31	-0.45
1 Month Lag	0.60	0.70	0.56	-0.29	-0.42
2 Month Lag	0.50	0.65	0.52	-0.27	-0.40
3 Month Lag	0.45	0.60	0.48	-0.25	-0.38

5. SUMMARY OF BAYESIAN HIERARCHIAL MODELS

Model	DIC	WAIC	Posterior Mean	95% Credible Interval
Model 1	1650	1680	0.12	[0.08, 0.16]
Model 2	1635	1675	0.15	[0.10, 0.20]
Model 3	1620	1660	0.18	[0.14, 0.22]

6. RESULTS FROM MACHINE LEARNING MODELS

Model	Accuracy	Precision	Recall	F1 Score	AUC
Random Forest	85%	82%	80%	81%	0.87
Gradient Boosting	88%	85%	83%	84%	0.90
XGBoost	90%	88%	86%	87%	0.92

7. SHAP VALUES FROM MACHINE LEARNING ANALYSIS

Variable	SHAP Value (Mean)	Impact on Dengue Incidence
Temperature	0.25	Positive
Rainfall	0.30	Positive
Humidity	0.22	Positive
Wind Speed	-0.15	Negative
Sunlight Hours	-0.18	Negative

8. SPATIOTEMPORAL DISTRIBUTION OF DENGUE CASES

Year	Region	Cases	Percentage of Total Cases
2020	Northern Region	250	18%
2021	Central Region	320	23%
2022	Eastern Region	280	20%
2023	Western Region	400	29%
2023	Southern Region	180	13%

9. CASE-CONTROL STUDY RESULTS

Variable	Odds Ratio (OR)	95% Confidence Interval (CI)	P-Value
Travel History	2.1	[1.5, 2.7]	0.002
Living in High-Risk Area	3.4	[2.8, 4.1]	<0.001
Occupation	1.8	[1.2, 2.4]	0.015
Use of Mosquito Nets	0.7	[0.5, 0.9]	0.043

10. PROSPENSITY SCORE MATCHING OUTCOMES

Group	Matched Pairs	Treatment Effect	P-Value
With Extreme Events	150	Increased by 20%	0.001
Without Extreme Events	150	No significant change	0.482

11. SENSITIVITY ANALYSIS OF MODEL PREDICTIONS

Scenario	Parameter Adjusted	Change in Model Output (%)
Increased Temperature by 1°C	Temperature adjusted by +1°C	Increase by 8%
Increased Rainfall by 10mm	Rainfall adjusted by +10mm	Increase by 12%
Decreased Humidity by 5%	Humidity adjusted by -5%	Decrease by 5%
Increased Wind Speed by 2km/h	Wind Speed adjusted by +2km/h	Decrease by 3%

12 SUMMARY OF PREDICTIVE MODEL PERFORMANCE (E.G., ROC, AUC)

Model	ROC	AUC	Sensitivity	Specificity
Logistic Regression	0.80	0.81	78%	75%
SVM	0.85	0.86	83%	80%
Neural Network	0.90	0.91	88%	85%

13. IMPACT OF EXTREME CLIMATE EVENTS ON DENGUE INCIDENCE

Event Type	Year	Change in Incidence (%)	P-Value
Cyclone	2019	+15%	0.001
Flood	2021	+12%	0.003
Heatwave	2023	+20%	<0.001

14. RISK FACTORS IDENTIFIED IN REGRESSION MODELS

Variable	Coefficient	Standard Error	P-Value
Temperature	0.28	0.05	<0.001
Rainfall	0.35	0.04	<0.001
Humidity	0.22	0.03	<0.001
Socioeconomic Status	0.12	0.02	0.015

15. COMPARATIVE ANALYSIS OF VARIOUS MODEL APPROACHES

Model	Strengths	Weaknesses	Overall Performance
Bayesian Models	Captures uncertainty, Robust	Computationally expensive	High
Machine Learning	High predictive power, Flexible	Requires large datasets, Interpretability issues	High
Spatiotemporal Models	Handles spatial correlations	May overfit with sparse data	Moderate

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