"The apex of all climate interventions"? Reducing vulnerability to extreme heat in urban West Africa with direct cooling technology through Mirrors for Earth's Energy Rebalancing (MEER)

Submitted to *Cities*, *Environmental Research Letters*, or *Climatic Change*

Benjamin K. Sovacool*[1234]

[1] Department of Earth and Environment, Boston University, United States

[2] Institute for Global Sustainability, Boston University, United States

[3] Department of Business Development and Technology, Aarhus University, Denmark

[4] Bennett Institute for Innovation and Policy Acceleration, University of Sussex Business School, United Kingdom

* Corresponding Author, Science Policy Research Unit (SPRU), University of Sussex

Jubilee Building, Room 367, Falmer, East Sussex, BN1 9SL

Phone: +44 1273 877128 Email: B.Sovacool@sussex.ac.uk ORCID: 0000-0002-4794-9403

Abstract: Extreme heat is a potent and progressively worsening public health problem confronting West Africa, where some have even called heat stress "the silent killer". Most heat wave deaths occur in cities, driven by the urban heat island effect. In wealthier cities, air conditioning is the primary means of adapting to extreme heat, but Sierra Leone has one of the lowest electricity access rates in the world, making this climate intervention unaffordable and unreliable. One novel intervention to extreme heat is solar radiation modification (SRM), also termed solar radiation management or solar geoengineering. SRM interventions, unlike climate mitigation or adaptation, can produce very fast results, they do not involve politically difficult legislation, can reduce the greenhouse gas effect, and involve modular and low-risk technologies. This study explores the history, benefits, and challenges of one SRM pilot project, Mirrors for Earth's Energy Rebalancing (MEER) in Freetown, Sierra Leone. MEER relies on a form of direct cooling technology to both reduce urban heat and increase albedo. To provide community benefits, MEER also makes furniture out of recycled PET bottles, which they give away at no cost so people can sit in the shade beneath the mirrors, alleviating exposure to extreme heat. The study is based on a mixed methods approach involving: (a) site visits across Freetown (N=8), including three "slums" or informal settlements where they are putting mirrors and reflective surfaces to the greatest potential use to help vulnerable women and children; (b) N=28 semi-structured interviews including community residents and members of local government; and (c) document analysis. In laying out the case study of MEER, the study aims to address a neglected focus on climate interventions to heat in urban areas in Sierra Leone and highlight the daily lived experiences of the poorest and most vulnerable residents of the city who struggle with extreme heat conditions.

Keywords: Freetown, Sierra Leone; urban heat island effect; direct cooling; passive cooling; extreme heat; heat resilience; solar radiation modification (SRM); climate adaptation; heat vulnerability

***Acknowledgments*:** This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Research Council (ERC) Grant Agreement No. 951542-GENIE-ERC-2020-SyG, "GeoEngineering and NegatIve Emissions pathways in Europe" (GENIE). The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s). Also, the project was approved by the Institutional Review Board at Aarhus University 2021-13 as well as by the Ethics Committee at the European Research Council. The author thanks Dr. Ye Tao for generously giving access to his colleagues and project sites so that this study could be completed. His commitment to open science and helping advance solutions to climate change in Sierra Leone is as uplifting as it is visionary.

1. Introduction

Thermal comfort—keeping warm in the winter, and cool in the summer—has repeatedly been shown to be one of the most valued energy services (de Dear et al. 2013; Djongyang et al. 2010). However, achieving thermal comfort in many urban areas is proving difficult, given exposure to extreme heat and future projections of global warming. A phenomenon exceedingly more dangerous and deadly than other climate change hazards, McLeod (2021) calls extreme heat the "silent killer" because it can strike without the same level of visibility as hurricanes or floods. More than a decade ago, Luber and McGeehin (2008) cautioned that general circulation models of climate change predicted that heatwaves would become more frequent and intense, affecting large urban areas not well adapted to them, causing significant health problems and weather-related mortality. More recently, Gabbe et al. (2024) acknowledge that heat is the deadliest weather-related hazard, and that those most exposed are people of color, those with lower incomes, seniors, young children, and those suffering from chronic conditions.

Critically, most heat wave deaths occur in cities, a well-evidenced result of the urban heat island effect. As Stone et al. (2010) note, cities have much higher ambient temperatures than surrounding areas, often exceeding 10°C, and caused by a multitude of factors. These include the loss of vegetation with accompanying loss of evapotranspiration, configurations of buildings that trap heat, the concentrated production of heat from vehicles and generators, and dark surfaces with low albedo (i.e., surface reflectivity), which absorb and then reradiate heat. Cities, in effect, become heat traps.

Consequently, extreme heat is a potent and progressively worsening public health problem in West Africa (Sylla et al. 2018; Kunda et al. 2024) In wealthier cities or those with less extreme climates, air conditioning is the primary means of adapting to heat waves, but it remains unaffordable for many of the most vulnerable, especially in less developed cities or those where electricity supply is intermittent, unreliable, or nonexistent (Jay et al. 2021). This is particularly true for West Africa, where electrification rates range from 8% to 42%, and in Sierra Leone especially, where the national electrification rate is about 26% in urban areas and 6% in rural areas, meaning "Sierra Leone has one of the lowest electricity access rates in the world" (Sustainable Energy for All 2021).

One unconventional intervention to extreme heat is solar radiation modification (SRM), also termed solar radiation management or solar geoengineering. SRM interventions, unlike climate mitigation or even adaptation efforts, have notable advantages: they can produce very fast results, they do not involve politically difficult fossil fuel legislation, they can reduce the greenhouse gas effect including water vapor, and they can involve modular and low-risk technologies such as brightening urban areas with cooler roofs and roads (Feinberg 2024). SRM can indeed cool the climate, and Harting et al. (2024) even estimate SRM can reduce mortality by over 400,000 deaths annually by 2080, with a possible range from −1.2 million to 2.7 million deaths annually.

This study explores the history, benefits, and challenges of one novel SRM pilot project, Mirrors for Earth's Energy Rebalancing (MEER) in Freetown, Sierra Leone. MEER relies on a form of direct cooling technology to both reduce urban heat and increase albedo. This form of direct cooling "has the potential to avert continued temperature rise in the near term and moderate at least some projected climate change disruption including extreme weather, sea level rise, loss of sea ice, glacier and permafrost melting, and coral reef die-off" (Baiman et al. 2024: 5). To provide community benefits, MEER also makes furniture out of recycled PET bottles, which they give for free so people can sit in the shade beneath the mirrors, alleviating exposure to extreme heat. The study is based on a mixed methods approach including site visits across Freetown (N=8), including three "slums" or informal settlements where they are putting mirrors and reflective surfaces to the greatest potential use to help vulnerable women and children; N=28 semi-structured interviews including community residents and members of local government; and document analysis.

In laying out the case study of MEER, the study aims to advance two interconnected contributions. Firstly, even though Global Soth cities face some of the most acute climate change risks, they remain the least discussed in the energy and climate policy literature, especially from the perspective of heat vulnerability. Macarthy (2012: 44) aptly made this point when writing that "whilst urban planners are increasingly being urged to develop robust and clear strategies for dealing with the impacts, in reality there is very little knowledge about the way the local context shapes whether, and how, planners and households are able to address the challenges posed … Moreover, since much of the literature on the response to climate change impacts has focused mainly on national level actions, there is very little knowledge about how such actions should be carried out in particular cities." In their global review of efforts to adapt to urban heat exposure, Laue et al. (2022: 8182) concluded that "heat stress remains an overlooked topic in comparison to other climate change adaptation needs." Pasquini et al. (2020: 1) similarly noted that "the heat-health relationship is an under-prioritized policy issue" within the literature on both Africa and cities. Confirming this point, although there is a growing list of seminal work on the climate impacts and hazards facing rural Sierra Leone, especially between farming and livestock cultivation (Lahai 2024; Sesay et al. 2022a; Sesay et al; 2022b Bangura et al. 2013; Oladele et al. 2024; Rahimi et al. 2020), heat exposure in urban areas remain a surprisingly neglected focus.

Secondly, the largest immediate beneficiaries of MEER are those living in extreme poverty within Freetown, meaning the study brings to light the lived experience of those struggling with vulnerability in the context of increasing weather extremes and with inadequate capacity for adaptation. Allen et al. (2020) argue that those residing in Freetown slums must suffer lives of extreme precariousness, and that almost the entire slum population (99%) is prone to natural disasters. Despite this precariousness, in the official assessment of climate risks from the Freetown City Council (2017), the word "heat" does not even appear in the entire 62-page report. Instead, it highlights flooding, erosion and landslides, deforestation, the degradation of bays and mangroves, and health risks from solid waste. Similarly, Turay (2022) explores the flood-management risks facing Freetown, but not that of extreme heat.

2. Case Study Selection and Methods

This section briefly introduces the case study selection of MEER and Freetown, Sierra Leone before explaining the research methods utilized.

2.1 Case study background

Freetown, Sierra Leone was chosen as the sole case study location because, as of 2024, it is the only place in the world where direct cooling in the form of MEER was being deployed (making case study selection straightforward).

The city of Freetown—the capital of Sierra Leone, a country in southern West Africa (see Figure 1)—is home to about 1.1 million people, located on a peninsula and a major port city on the Atlantic Ocean, where it generates about one-third of the country's entire Gross Domestic Product, despite having only 15% of the country's population (Van Assen 2022). It was established in 1787 as a British colony for settling freed slaves, and it currently serves as the oldest municipal government in British West Africa, where it is governed by both Local and Central governments (Macarthy 2012). Freetown possesses a total land area of about 357 square kilometers with a coastline of about 40 kilometers, and these feature two very distinct topographic zones: one of coastline, low-lying areas and raised beaches, and another of elevated land and hills rising to Freetown Peninsular Mountain.

Figure 1: Map of Sierra Leone and the capital city of Freetown

Source: Lynch et al. 2020. Note: CBD=central business district.

Freetown has several distinctive attributes as an urban area. Infrastructural development virtually came to a standstill during the civil war between 1991 and 1998 (Freetown City Council 2017). It has very high rates of population growth and migration: Both during and since the country's civil war, some 500,000 farming families were displaced nationally, with many relocating to the city (Lynch et al. 2020). The city lacks many basic services such as reliable electricity and water, with even the Freetown City Council reporting in 2019 that the city is "sprawling and fragmented" and that "about 95% of the city's population does not have access to mains water" (quoted in Lynch et al. 2020: 12). Moreover, Freetown has suffered from several recent and serious natural disasters including flooding, landslides (one on August 14, 2017, left more than 1,140 dead and 3,000 homeless), and a deadly outbreak of the Ebola virus in 2014 and 2015. Macarthy et al. (2024) note other problems facing Freetown such as a scarcity of affordable and reliable housing, lack of fresh food and unhealthy diets, and limited access to educational institutions for youth because of financial constraints. An estimated 80% of city residents live in slum conditions. Most relevant for this study, Freetown also is the first city in Africa to have a chief heat officer, appointed in 2021, to make the city "cleaner" and "greener," a role currently occupied by Eugenia Kargbo (Dinneen 2023).

Mirrors for Earth's Energy Rebalancing (MEER) is a form of SRM known as direct climate cooling, or more colloquially, direct cooling (see Table 1) (Baiman et al. 2024). MEER has the advantage of offering both SRM as well as thermal radiation management, lowering urban and surface temperatures. MEER involves deploying mirror arrays on the Earth's surface to reflect excess downwelling solar radiation and to focus on outgoing thermal infrared radiation to decrease local temperatures. The MEER project team has been working in Sierra Leone since 2023, experimenting with passive cooling techniques for underdeveloped settlements. Smaller scale experiments have shown that housing within Kroo Bay can be cooled by up to 7 degrees Celsius with the right adaptations. Currently, the team is working on developing a much larger project in the Aberdeen region of the capital city, which will focus on community scale cooling and the amplification effect.

Table 1: Classification of approaches to direct climate cooling

Approach	Category	Active elements	Medium
Afforestation, Reforestation, and Soil and Vegetation Restoration	TRM	Terrestrial biotic pump	Land Evapotranspiration
Buoyant Flakes	SRM	Phytoplankton	Water albedo
Cirrus Cloud Thinning	TRM	Ice nuclei	Cirrus cloud cover
Fizz Tops (Fiztops)	SRM and TRM	Nanobubbles	Water albedo and evaporation
Ice Shields to Thicken Polar Ice	SRM	Ice and snow	Ice and snow albedo
Marine Cloud Brightening	SRM	Seawater mist	Cloud albedo
Mirrors for Earth's Energy Rebalancing (MEER)	SRM and TRM	Mirrors	Land and still water albedo
Mixed-phase Cloud Thinning	TRM	Ice nuclei	Reducing cloud cover
Ocean Thermal Energy Conversion	TRM	Sea surface heat	Heat to hydrogen conversion and reverse heat pump

Seawater Atomization	TRM and SRM	Sea water and seawater droplets	Sea water evaporation and cloud cover
Stratospheric Aerosol Injection	SRM	Aerosols	Stratospheric albedo
Surface Albedo Modification of Ice and Snow	SRM	Reflective materials	Ice and snow surface albedo
Tree Planting and Reflective Materials	TRM and SRM	Plants and ground water and reflective materials	Land Evapotranspiration and sunlight reflection
Tropospheric Aerosol Injection	SRM and TRM	Increased cloud condensation nuclei and photocatalytic sources of oxidative radicals.	Increased cloud reflectivity and methane removal

Source: Modified from Baiman et al. (2024). SRM= solar radiation management; TRM, thermal radiation management.

2.2 Qualitative research design

The research design for studying MEER is based on original interviews, site visits, and document analysis.

First, 28 semi-structured interviews were conducted in November and December 2024. These interviews all focused on the same set of general questions including the history and background of the MEER project, its expected benefits, its challenges, and its lessons for policy. Semi-structured interviews employed a "snowball" effect by developing contacts and interviewing people in connection with the MEER project or climate change adaptation and city planning in Freetown, Sierra Leone. The sampling of respondents was purposive and solicited through the MEER website as well as the canvassing of neighborhoods and sites of community activity such as local businesses and markets. Table 2 provides an anonymized list of all 28 respondents. To protect the identity of our respondents, we refer to these only generically by type (*e.g.* their institution) and respondent number *(e.g.* SL3). Each interview lasted generally between 15 and 120 min.

Table 2: Overview of semi-structured interview respondents for this study (N=28)

Respondent N	Institution	Date
SL1	MEER	11/11/2024
SL2	Freetown City Council	12/15/2024
SL3	Ministry of Local Government and Rural Development	12/15/2024
SL4	MEER	12/16/2024
SL5	MEER	12/17/2024
SL6	MEER	12/17/2024
SL7	MEER	12/17/2024
SL8	MEER	12/17/2024
SL9	MEER	12/17/2024
SL10	MEER	12/17/2024
SL11	Building occupant/resident	12/17/2024
SL12	MEER	12/17/2024
SL13	Building occupant/resident	12/18/2024
SL14	Building occupant/resident	12/18/2024
SL15	MEER	12/18/2024
SL16	Kroo Bay Community Council	12/18/2024
SL17	Kroo Bay Community Council	12/18/2024
SL18	Building occupant/resident	12/18/2024
SL19	Building occupant/resident	12/18/2024
SL20	Building occupant/resident	12/18/2024

SL21	Building occupant/resident	12/18/2024
SL22	Building occupant/resident	12/18/2024
SL23	Building occupant/resident	12/18/2024
SL24	City government	12/18/2024
SL25	Ministry of Health and Sanitation	12/18/2024
SL26	Aberdeen Community Council	12/18/2024
SL27	MEER	12/18/2024
SL28	Building occupant/resident	12/18/2024

To complement the interviews and match stated preferences with a type of revealed or observed preferences, the research team members also conducted a total of 8 site visits, some of which are shown in Figure 2. Site visits included Juba Hill, where MEER staff were setting up an experiment; Aberdeen Roundabout, the site of a skills training workshop; Lumley Roundabout, where the MEER team was erecting a shade over a community pavilion; Kroo Bay, the largest informal settlement in the city where MEER is currently deployed; Freetown City Hall; Crab Town informal settlement; and Kingtom, another informal settlement and landfill. Each of the naturalistic site visits lasted between 20 and 180 min.

Figure 2: Overview of site visits and important locations visited in Freetown, Sierra Leone

A B

C D

E F

Source: Author. Panel A shows the Freetown harbor. Panel B shows the central business district. Panel C the informal settlements of Aberdeen. Panel D shows the informal settlement of Kroo Bay, Panel E Crab Town, Panel F Kingtom.

Finally, to triangulate the data from the interviews and site visits, our study is supplemented with an analysis of externally oriented presentations and reports, city planning documents, academic journal articles and other sector-specific publications. While these materials are not exhaustively cited in the references, they are implicitly leveraged to reinforce and support the detailed analysis of the interview and site visit data.

3. Results and Discussion

Drawing from its three sources of data—interviews, site visits and document analysis—this section presents our results across the themes of lived experiences of heat exposure, explaining to readers the dynamics of MEER's approach to address it, its benefits, and its challenges.

3.1 Lived experience of extreme heat exposure

Freetown, Sierra Leone is a city that almost never cools down, due to its equatorial location and little seasonal or daily variation in temperature. Although Freetown is located on the coast, it is essentially a topographic trap for heat, given it experiences very high temperatures, heavy precipitation and high humidity given a wet tropical climate (McCarthy 2012). These topographic and climatic features make Freetown "highly vulnerable to extreme heat" (Atlantic Council 2023: 3), especially given that more than 90 percent of work hours for most residents are undertaken in non-climate-controlled conditions. McSweeney et al. (2008) calculate that between 1960 and 2003, mean annual temperature in Sierra Leone have already increased by 0.8°C, and over the same period, the number of "hot" nights has risen significantly at an average of 38 nights per year. Despite its precipitation and high humidity, the city also suffers from frequent droughts, especially during the dry season from November to April (Mustafa et al. 2021). Perhaps confusingly, extreme heat poses a risk throughout both the dry and wet seasons. During the dry season, heat magnifies drought, and higher temperatures increase the evaporation of moisture from soil and contribute to wildfires and shortages of freshwater; in the rainy and wet season, higher temperatures sustain ideal conditions for mosquitos to breed and spread malaria, making farmers and other outdoor laborers more susceptible to heat stress (McLeod 2021).

Other factors play a role in heat vulnerability as well. Van Assen (2022: 2) adds that "Freetown is one of the world's most vulnerable cities to the effects of climate change," given a confluence of rapid population growth, poor quality of infrastructure, suboptimal city planning, an inadequate social services such as transport, education, and healthcare. These trends also converge to facilitate a substantial increase in the number of informal settlements, or "slums," because of lack of affordable housing. As of March 2020, at least 68 informal settlements existed in Freetown, home to about 35% of the city's population (McLeod 2021). Troublingly, these slums are often located in areas most risk-prone to climate hazards including flooding, landslides and extreme heat. An estimated 38% of built-up expansion across Freetown from 2000 has taken place in areas at medium or high risk to climate change (World Bank 2018). The World Bank (2018: 2) also cautions that "Freetown's current economic and social

infrastructure is dilapidated, and basic service delivery has fallen short of population growth" and that "Freetown is, and will likely remain, the most affected by the prevalent disasters in Sierra Leone." The city and national economy face uniquely high exposure to heat as both rely on labor-intensive production with more than 90 percent of working hours vulnerable to heat; the Atlantic Council (2023) argues that the impacts of these losses will bear most heavily on the poor.

Our lived experiences data confirmed these trends repeatedly. Traditional roofs on slum buildings, shown in Figure 3, contribute to the problem of heat exposure as they are akin to what SL28 called "*living in an oven*", or SL1 termed "*sleeping in a perpetually baking cinder block*." SL2 also stated that "*I hate the heat in Freetown, I hate living in it, it is so damn hot all the time, with no shade given big trees have all been cut down or washed away, temperature in the winter months literally doubled from what it used to be when I grew up here*." SL18, who resided in Crab Town, said that "*I hate it when it's too hot, I get exhausted just breathing and sitting still*." SL19 spoke about it being so hot they "*cannot breathe, cannot sleep, my whole family sand I develop heat rashes or heat stroke*," after proceeding to show the author multiple skin rashes on their arms, back, and legs. In Kroo Bay, a single slum home to about 37,000 people, SL17 stated that conditions were so poor, during heat waves women literally will sell themselves sexually for water: "*life here is very different than in Europe or America, here we have no drainage systems, no toilets, no mains water, with waste everywhere, it is honestly … heartbreaking during heat waves that women will even offer sex for water, they are so desperate and thirsty*." SL21 explained that "*here in Kroo Bay, we cannot even afford simple interventions like an electric fan, with if we had reliable independent power supply, it would be too expensive, more than many months' wages*."**Figure 3: Exposure to metal roofs and extreme indoor heat in Freetown, Sierra Leone**

A B

C D

Source: Author. Panel A shows a typical roof in Aberdeen. Panel B shows Murray Town. Panel C Kroo Bay. Panel D Crab Town.

That informal settlements ("slums") have elevated exposure to heat given compact buildings, population density, and metal roofs has been confirmed by other researchers globally. Mukhopadhyay et al. (2021) have found that metal roofs absorb and radiate large amounts of solar heat, leading to drastically hotter indoor temperatures, particularly during heat waves, putting people at risk of heatstroke and other health complications; this is especially problematic in areas with limited access to cooling systems and water. This means even under similar outdoor conditions, indoor heat stress is often worse in slum dwellings than in rural villages or urban homes. Adegun and Ayoola (2022) have documented "intra-urban inequality in heat exposure and adaptation" in other African cities such as those in Nigeria, noting that those in slums lack adequate capacity to cope with heat compared to those who are more affluent, and those who can afford to modify their dwellings with air conditioning, shady plants, or ceramic tiles to lower indoor heat. In Kenya, measurements of temperature and a thermal comfort have confirmed that slums are several degrees Celsius hotter than other city areas, and that these temperature increases contribute to increased mortality of several percent in youth and elderly populations (Scott et al. 2017). In Uganda, slums suffer from the greatest lack of shade and vegetation which also contributes to their being many degrees warmer than other regions of cities (Van de Walle et al. 2022).

Unfortunately, multiple independent projections and forecasts indicate that, without future interventions, these trends of heat exposure and vulnerability will only worsen. Rohat et al. (2019) forecast future heat exposure across 173 large African cities and demonstrated that the aggregate exposure in African cities will increase by a multiple of 20–52, reaching 86–217 billion person-days per year by the 2090s, depending on the scenario, with the most exposed cities are located in Western and Central Africa, which is where Freetown resides. Focusing on Freetown specifically, the Atlantic Council (2023) estimates that by 2050, about 120 days, or four months, every year will be as warm as the hottest ten days currently. They also project that by 2050 heat and humidity related losses in labor productivity will double, and that heat-related losses to the local economy will grow from US$9 million now to more than $45 million by 2050. McSweeney et al. (2008) projected that by the 2060s, the mean annual temperature of Sierra Leone will rise by between 1.0-2.6°C and will further increase by 1.5-4.6°C by the 2090s, and that the number of hot days everywhere will increase by 26-63% by the 2060s and by 37–84% by the 2090s. Tarawally et al. (2018) confirm that maladaptive behavior continues to worsen exposure to heat in Freetown as well, given that the local population continues to clear trees and vegetation for fuelwood or housing, further exposing residents to heat stress.

3.2 Mirrors for Earth's Energy Rebalancing (MEER)

MEER (Mirrors for Earth's Energy Rebalancing) is a nonprofit organization dedicated to addressing heat exposure in Freetown, via direct cooling interventions that can mitigate local, and eventually global, temperature increases. SL1 explained the genesis of MEER as follows:

> *MEER begins at Harvard University as a sort of student project, founded in 2020 or 2021, when Dr. Ye Tao was learning about heat exposure in African cities but was running a nanotechnology lab, working on medical microscopes and improvements. Dr. Tao had many ideas, not just surface reflectors, but also ocean acidification, other things as well, generating electrical power with renewables. He got students together, situated globally, made it into a learning process for students, and MEER was born, to facilitate teaching, mentoring, and adapting to local heat stress.*

SL4 adds that "*while MEER could have been piloted in any number of least developed countries, we chose Freetown and Sierra Leone because it has the first chief heat officer in Africa, and we became aware of the city's heat vulnerability through a heat mapping campaign being managed by the American National Oceanic and Atmospheric Administration … it began with a 6 week small demo project in early 2023, and we have been operating here ever since*."

The centerpiece of MEER's approach to heat stress utilizes surface reflection technology to cool metal and tin roofs. Such roofs are intended to be easy to install, affordable, and manufactured from recycled materials, when possible. As SL1 explained:

> *MEER's cool roofs incorporate solar-reflective sheeting or paint, materials that help to transfer heat off a structure, preventing excessive sun radiation absorption and reducing internal temperatures by 6-7°C. This reduces energy consumption by decreasing the need for cooling systems, resulting in lower greenhouse gas emissions. Moreover, the construction of these roofs provides sustainable employment opportunities for low-skilled workers across Freetown.*

SL1 and SL4, and SL5 all spoke about how MEER involves different materials as well as different roof coatings, from ordinary roofs modified with local paint, to simple aluminum mirrors, to new roofs of zinc coated with iron, to even new nanomaterials with silicon and alumina mixed into locally sourced white paint to increase their emissivity. SL4 expanded upon other unique elements of MEER's approach:

> *MEER can use very targeted forms of SRM to the point where I don't even call it SRM, we have a much better handle on managing thermal heat, so I like to call it radiative thermal management … SRM only focuses on visible light, but emerging material science allows you to work on visible light and an infrared portion of light ... And that ability to simultaneously address both portions of the spectrum is missing traditional geoengieering such as stratospheric aerosol injection. These are only working on the short-wave components, and they have a long wave penalty, meaning that the mere existence of any particles in between the ground and space impedes the rates of infrared emission back to space. In simpler terms, MEER gives you more control knobs to control radiation and temperature than approaches that only work in the stratosphere, with limited spatial control.*

This statement suggests that in addition to lowering heat, MEER can contribute to increasing the earth's albedo by reflecting more solar radiation back into space.

In designing MEER this way, respondents spoke about how their intent was to utilize scalable, simple and modular technologies that can be deployed at very targeted, small scales. SL1 clarified that:

> *MEER underscores that you can have meaningful applications on an extremely small scale, no one is going to try and do stratospheric aerosol injections over one city block, whereas you can do this with mirrors and reflectors even down to a single piece of roof. With MEER, you can deploy it in these small-scale applications that have a huge impact on peoples' lives, see if and how it scales.*

Another underlying attribute to MEER's approach is to use technologies and materials appropriate to Freetown's climate and political economy. SL12 remarked that "*Freetown already has programs to reduce urban heat, including a heat week and a Cooldown Freetown program, at some point they made a public show of planting trees and other interventions such as shading devices in market areas, but these were not reflective, didn't work very well, started to fall apart, and the trees died. So I believe that MEER is using technologies much more appropriate to local culture and context*."

In addition, MEER's approach involves a gradual, stepwise, phased in perspective on deployment. SL4 elucidated three essential phases to MEER. The first phase began in 2023, starting with placing MEER technology on five large buildings, three residential ones and a school in Kroo Bay, with single point indoor air temperature measurements. The second phase, running 2024 and into 2025 (right now), involves expanding to 6 more buildings in Kroo Bay, large residential ones, with more optimized sensors within the building or even within a room, as many as 8 sensors in one room, to get more refined measurements, as well as expanding measurements beyond Kroo Bay into places such as Aberdeen and Crab Town. The third phase, post 2025, will focus on decreasing costs, better materials, and increasing the number of buildings where deployment occurs to "*as many as possible*," potentially even to all of Kroo Bay or all informal settlements.

In addition to its technical innovation, MEER also features some innovations in business model and institutional structure. SL7 framed MEER as an umbrella consisting of three core parts: a data and experimentation component, where MEER advances basic science, records measurements, and builds knowledge; a design and fabrication component, where they put those learnings into engineering new materials and devices; and a community outreach and capacity building component, where they train local people in skills and also do other things for the community such as making furniture out of recycled PET bottles, or putting up shades over roundabouts and parks for community use, for free. SL1 confirmed that MEER is "*not about profit, or making money*," positing that:

> *MEER is entirely funded by donations and grassroots efforts. We have never yet had any major funding from a corporation or government. Many who work with us do so voluntarily, as teachers. MEER has no commercial*

aspirations; we are not in this to make money. Instead we are about helping others with no direct financial gain, the only agenda we have is to make a difference, to get knowledge out there … things like MEER can have a rapid, immediate impact, with the fewest side effects, it ticks all the boxes, well all the boxes except for one, getting rich, but maybe that's also an important box.

3.3 The perceived benefits of MEER

The prospective benefits of MEER can be classified into local, community, and global dimensions. Local benefits refer to those that accrue directly to adopters, such as enhanced indoor comfort and safety, the reduction of energy bills, and extended roof service life. Community benefits refer to those that benefit the entire neighborhood and city, such as reducing the urban heat-island effect, training and skills, and improvement to public health. Global benefits refer to those that extend beyond Freetown to encompass the advancement of science, future applications involving agriculture, forestry and freshwater conservation, and the ultimate goal of sustained global temperature reduction.

At the local dimension of adopters, MEER is resulting in enhanced thermal comfort, reduced heat stress, and improved living conditions. As SL1 highlighted, "*cool roofs significantly improve indoor comfort and safety in non-air-conditioned areas by reducing heat transfer from the roof, creating a much more pleasant environment during hot weather conditions and a far better quality of life for occupants*." SL7 agreed and confirmed that to them the most significant benefit of MEER was "*immediate, drastic cooling*" for homes within Freetown's slums. SL11, who lives within a building equipped with MEER interventions, stated that "*Before MEER, life in my home was boiling, imagine living inside a kitchen stove, sweating all the time, being unable to sleep, unable to keep food, causing our water to disappear, and fires. Now, life is good."* SL8 stated that with MEER, residents "*don't feel any form of heat, they can sit and not even need a fan, it's so cool and comfortable*." Field experiments from MEER so far have shown indoor air temperature reduction by up to 7°C, reduction of evaporative freshwater loss by up to 90%, and reduction of soil surface temperature by 10°C (Baiman et al. 2024). Figure 4 shows one building equipped with MEER technology where indoor temperatures were about 5°C cooler than in other buildings, and this was during the peak of winter, in December 2024. SL15 noted that in places such as Kroo Bay, MEER is functionally the only intervention capable of delivering thermal comfort: "*Freetown needs cooling solutions within the range of affordability for Kroo Bay residents, the urban poor cannot afford a fan, yet alone the electricity to run it, or something as fancy as air conditioning, there are no other alternatives to MEER at that cost and scale, none*."

Figure 4: Application of MEER technology confirming reductions in indoor temperature in Kroo Bay, Freetown, December 2024

A B

C D

Source: Author. Panel A shows MEER's founder Dr. Yao Te inspecting a MEER roof in Kroo Bay, Panels B and C a comparison between buildings with and without MEER interventions. Panel D shows indoor temperature monitoring confirming reductions in temperature.

Other related local benefits to MEER involve reduced energy bills, for those that can pay them, and the extended service life of roofs. Cool roofs minimize the need for air conditioning, resulting in the potential for large energy bill savings. By reducing cooling demands, older and inefficient air conditioning systems can still provide adequate cooling during hotter summers. Cool roofs also contribute to lowering roof temperatures, which can extend the lifespan of the roof, involving less wear and tear, and adding value to the building. SL4 confirmed this when noting that "*MEER roofs delay the onset of oxidation, in some cases doubling the lifetime of the roof, meaning they become over time cost negative for the user in the urban environment*."

Because of these immediate local benefits to MEER, multiple respondents spoke about its strong acceptance among adopters. SL4 stated that:

The beauty of operating in Freetown is that for every square meter you deploy you benefit more people, the public acceptance rate is basically 100%, you can convert not just buildings but whole neighborhoods, a huge advantage compared to Tanzania (where we've done a school) or India (where only 50-70% buy in), makes deployment imperfect, Freetown is the only place where 100% is possible.

SL9 said that "*post occupancy reports indicate 100% success, everyone who has adopted a new roof is happy*". SL11, an adopter, articulated that "*I have no complaints, I am a 100% supporter of MEER and everyone I know is too*." SL13 and SL14, both beneficiaries from MEER interventions, also commented that "*we like it*" and "*bravo, respect to MEER*." SL1 also confirmed that "*MEER is being deployed at no cost to communities, we do it for free, we offer cooling at no charge to them, this is why have broad buy in from people, who welcome the intervention, along with support from local heat officers, schools, and community leaders*."

At the dimension of the community and city, the most salient benefit was a reduction in the urban heat island affect. SL9 affirmed that "*even at our current smaller scales of deployment, MEER is helping the entire city from rising temperature, through*

passive cooling technology and abating heat stress." Because many of MEER's solar reflector devices are upcycled from glass bottles, aluminum cans, and PET packaging, there are added environmental benefits to the city as well, in addition to MEER's focus on outreach and capacity building. Figure 5 for example illustrates two MEER projects where they are training local people to convert plastic waste into shaded benches (which are free to everyone to use), and also building community pavilions with shade to reduce heat exposure. SL4 explained how "*in addition to lowering heat stress, we also teach community members how to make furniture and community pavilions shaded with our technology, this includes 3 months of training, and we offer to cover all transportation and food for our trainees*." SL12 spoke about how "*I love the training program, it is very creative, and I learn something new every day, no other job offers this in all of Freetown*". SL26, a member of the Aberdeen Community Council, even suggested that to them, the "*skills and training MEER provides far outweigh in my mind the benefits of direct cooling*."

Figure 5: Community workshops and pavilions being equipped with MEER technology in Aberdeen, Freetown, December 2024

A B

C D

E F

G H

Source: Author. Panel A shows the sawing of local wood, Panel B the upcycling of PET bottles. Panel C shows the weaving of those PET bottles into mesh, and their assembly into a bench, shown in Panel D. Panels E and F show the construction of a shaded pavilion for community use. Panels G and H local assembly of MEER roofs at their headquarters in the central business district.

Beyond capacity building and skills, other respondents spoke about community co-benefits such as enhanced public health and reduced rates of malaria. SL4 spoke about how there was less strain on the hospital and public health sector in Freetown due to MEER, given that during some heat events, "it is impossible for humans to survive when temperatures exceed 40 degrees C, the human body is placed under extreme conditions and heat stroke, meaning MEER is literally keeping people out of the hospital." Jay et al. (2021) refer to this as "the heat cascade," noting that excess heat from the urban level is transferred to the building level and then the individual level, progressively worsening the heat stress a person must physiologically manage both indoors and outdoors during hot weather. McLeod (2021) also contends that heat illness can exacerbate chronic heart and lung-related ailments, and that the lives and livelihoods of young children, the elderly, pregnant and nursing women, disabled individuals, and informal outdoor workers are disproportionately impacted by urban heat—all something MEER can alleviate.

An added health benefit involves vector borne diseases such as malaria, and poisoning or death from severe storms. SL15 explained that without MEER interventions, many Kroo Bay residents sleep outside without misquote nets or beds where they are more prone to contracting malaria; with MEER, it is cool enough to stay inside and sleep safely. SL11 added that "in the wet season, heat spreads disease and makes my family sick when we sleep outside." Lastly, MEER roofs have other environmental health benefits given that they do not rust and degrade as traditional roofs, nor do they leach pollutants into the environment from corroded metal, such as the materials shown in Figure 6. SL4 added that during severe storms, these traditional walls and roofs can even come apart, injure and kill people.

Figure 6: Degraded, unsafe and rusty housing infrastructure in Crab Town, Sierra Leone, December 2024

Source: Author.

Given its community benefits, MEER also has the support of local and national government, and at times, the even more important level of government at the neighborhood level. SL4 affirmed that:

> *One key to our success has been deciding that while local government such as the Freetown City Council and national government are important, they are less important than the local chairman of the roundabouts, local community leaders who act as chiefs, we have them as highly engaged partners in all of our projects.*

Indeed, during the site visits the author undertook, local and city officials were visibly pleased to see MEER at work, indicating a strong level of trust. Perhaps cleverly, MEER has also offered to repair the roof of the city council for free, after a storm, and gives some of the swing benches and furniture to the police to use for free. The author even witnessed the Commissioner of Police for Freetown give MEER experts a big hug before posing for multiple photographs.

Global benefits involve the advancement of climate science, future applications across other sectors, and the longer-term vision of achieving significant temperature reductions worldwide. Despite heat posing as a "silent killer" in African cities, little is currently known about direct cooling science. SL1 commented that "*MEER is helping fill research gaps in how we understand urban albedo and heat exposure*," and SL4 expanded upon this claim to argue that even fundamental science is lacking in some of the areas within MEER's remit:

> *You may be surprised that even the basic science for SRM and direct cooling doesn't exist, and part of our work is to enable a fundamental mechanistic understanding, especially at the very basic level of the single building structure … Last*

year we looked at only four buildings, and which materials controllably increase reflectivity. But we haven't expressly engineered the infrared mission component.

Indeed, to help partially fill this gap, MEER was running an experiment shown in Figure 7 when the author visited that was undertaking direct measurements of surface temperatures on different roofing types, coatings, and materials. Baiman et al. (2024) add that beyond the level of buildings and cities, cloud feedback and circulation impact at and beyond regional scales remain to be experimentally evaluated, something else MEER seeks to achieve.

Figure 7: A MEER experiment testing the surface temperatures of different materials in Juba Hill, Freetown, December 2024

Source: Author. The experiment showed that the normal roof, rusted and dark, had a surface temperature measured above 60°C. The material with white paint measured a lower temperature of 45°C. The most advanced material, with a shiny 50 nanometer thin film of aluminum over a plastic 70 micrometer PET sheet, measured a surface temperature of only 36°C.

Respondents identified other prospective global applications of MEER technology that could aid agriculture, water management, forestry and fire prevention. MEER technology could, according to SL4, be used to drop ambient temperature within greenhouses, avoiding overheating, or to benefit agriculture by letting in photosynthetically active light, but rejecting all other light harmful to plants, increasing plant growth and reducing water consumption. SL1 spoke about how MEER could be "*applied to areas like reservoirs and canals to guard against evaporation, or widely utilized in farming applications, to keep temperature down to stop plants harm from excessive heat and water irrigation process, an use reflection that shields from above and also bounces light from underside of the plant to improve yield, all kinds of applications, a global heat reducing proposal*." SL4 noted the potential for "*substantial amounts of water savings"* within hydroelectric reservoirs, something especially useful in areas of water scarcity, and a potential application in forestry where it could be used to reduce drought and enhance fire protection. Baiman et al. (2024) report preliminary data suggesting evaporation suppression by 40% at 50% mirror coverage and water cooling up to 10°C, with significant potential for large mirror arrays over freshwater bodies such as reservoirs, rivers, and aqueducts.

These benefits, moreover, pale in comparison to the ultimate longer-term vision of MEER, which is to become widely deployed to sufficiently reduce the impact of global warming. SL1 said boldly that "*our primary mission is to restore the Earth's energy balance by the end of the century, effectively combating climate change*." SL4 agreed and noted that "*MEER offers one of the best options, at super large scales, for managing energy balance, even more effective than other interventions than adaptation or mitigation*." SL6 spoke about their vision of "*going to all of Freetown and then beyond, the goal is truly largescale deployment*", SL8 that they *"want to see MEER as the apex of all climate interventions, used everywhere*", SL10 that "*I want to target and reach 80% of the world population with MEER technology*." These statements are confirmed by some emergent evidence within the scientific literature. Tao (2019a) writes MEER could be used to save collapsing ecosystems and offset global warming at scale, claiming that "the inconvenient truth of cooling by anthropogenic aerosols renders the sum of incremental adaptation measures insufficient, regardless of implementation scale and speed of implementation, for halting an ongoing extinction of complex life on this planet." Baiman et al. (2024) contend that "optimally oriented stationary surface mirrors, enhanced with a top layer of spectrally selective infrared emitter, are estimated … to have the potential to reduce the net top of the atmosphere flux by 70 W/m^2 on average." As evidenced in Figure 8, this would suggest MEER is a more effective geoengineering option than negative emissions technologies such as direct air capture or other forms of SRM.

Figure 8: Viability and optimality of climate change geoengineering options

Source: Tao (2019b)

3.4 The perceived challenges facing MEER

The challenges facing MEER also exist across local, community and city, and global levels. Local challenges include corruption, poverty and theft. Community challenges include possible negative side effects of deployment and lack of local capacity. Global challenges include an epistemic bias against SRM and land constraints to global deployment.

Local challenges involve corruption, theft and poverty. Instances of corruption were witnessed during the site visits and arose during the interviews. This included an unnamed new principal of a school demanding money to use his roof, in violation of an agreement with the previous principal, with the new principal proceeding to destroy MEER's research devices and data when they refused to be extorted and pay. The author met an ex-Employee met (but did not interview them), who had been let go from MEER for theft of materials and devices. MEER made an offer to the police station to repair their roof, damaged in a cyclone, for free, but this offer was declined so that a government linked company could do it for profit. It also included the

stealing of MEER designs for benches and shaded swings that would have been free, but that task went to another contractor who did them for profit—so poorly that they fell apart a few weeks later.

Another local challenge is the intertwined one of theft and poverty. SL5 remarked that "*oddly as much as they can support us, the citizens of Freetown can also become a barrier, when some people remove our sensors and sell them to buy mobile phones or, worse, drugs*." SL4 admitted that:

> *A big barrier for us is poverty and theft. People keep stealing our sensors that measure temperature and humidity, which cost us about $20, but people are so poor they steal them to make another $1-2. This is complicated by a serious drug addiction problem, boys suffering and see a stolen sensor as key to their immediate relief, every day here there are dozens of deaths from overdoses.*

When the author visited Crab Town with SL27, they had placed 600 sensors in the Crab Town Community, but they estimated that *half or more* had already been stolen

At the community level, some possible negative environmental impacts exist alongside lack of local capacity as challenges. Because MEER devices modify the light spectrum, SL4 ruminated that they could, in theory, affect plants and biodiversity negatively:

> *One thing that I'm particularly worried about is how surface reflection technology could absorb enough UV light, or scatter it, to drastically change what reaches the surface. Organisms go to great lengths to evolve UV resistance, skin color, plants have like a repair machine to deal with UV damage. And let's say we tune down the UV sufficiency that over a few generations of plant live or phytoplankton life, they have a loss of function mutation to get rid of that UV resistance, because in general cells or organists like to get rid of useless stuff in evolution … If that loss function mutation happens and then spreads to the whole population, then one day we stopped doing the intervention, the ecosystem has lost its ability to cope with UV light, and that could risk a population level potential expiration on larger spatial scale. So that's a just one example of what can happen in the biology, which we don't fully understand … there is simply no experiment to really allow us to anticipate what could happen at the population level over multiple generations*

Another community challenge is lack of local capacity. SL4 again explained that:

> *Freetown is an intrinsically challenging environment to operate in. Sustained education of staff is lacking, physicists and engineers are really at only a middle school level on the theoretical side, even though they graduated from college here in Sierra Leone. Here in Freetown there is no lab, no materials, zero hands on experience, so it is a significant challenge to get them to perform university level research in a more complex laboratory environment.*

SL1 adds that MEER also has little appeal for those not affected by extreme heat, noting that "*a large community barrier is ignorance, if a city hall person, governor or mayor, personally doesn't need a cooler home, they probably won't care to move along interventions to extreme heat, they won't see the need*."

A final community challenge is that even if MEER were scaled and implemented across Freetown, it would be insufficient, by itself, to address all climate hazards, especially those related to flooding, severe storms, landslides, and disease epidemics, which could all damage MEER technology and/or its human technicians. MEER would need to be integrated with other forms of climate adaptation—such as mangrove conservation, diversification of livelihoods, improved water and sanitation, and better healthcare, to name a few— to fully build resilience (Lambert et al. 2021). As Figure 9 shows, issues of sanitation and water as well as coastal protection are particularly acute in Freetown's slums, especially Kroo Bay and Crab Town.

Figure 9: Coastal erosion, unsanitary conditions, and polluted water in Kroo Bay and Crab Town, Freetown, December 2024

Source: Author.

Lastly, at the global level, challenges include a stigma against SRM and land constraints to global deployment. Stigma and epistemic bias against SRM exist even at the level of scientists. SL4 explained it as follows:

> *I think very few people can see the full picture or have the skill to understand a holistic view of the science of SRM. People, even scientists, have this visceral reaction against SRM. For many of my colleagues, they don't understand why I just don't plant trees, even as the evidence points to their limited survivability in an environment like Freetown. Very few people globally look seriously into the science of SRM. If you're plant scientists looking at carbon capture through your leaf stigmata, you probably don't think about the concurrent latent heat production. They stay at the top of their game in biology, but believe they know enough to still oppose SRM even though it's not their field.*

SL9 added that "*globally we need more awareness, more acceptance of SRM as a technique, it is not widely accepted, people have preconceptions and biases we have to always fight against*." There are also obvious constraints to global deployment of

MEER technology, even if all urban areas were covered it would never reach the level needed for global temperature reductions more than 1°C.

4. Conclusion

Although only launching its novel form of direct cooling and surface reflection technology in Freetown, Sierra Leone in 2023, MEER (Mirrors for Earth's Energy Rebalancing) is already having a material impact at lowering vulnerability in one of West Africa's most vulnerable cities to extreme heat. Respondents and community leaders interviewed for this study spoke about heat so stifling it was difficult to breathe within their homes, described as like living in an oven, yet alone sleep or work. MEER is deploying more resilient, affordable, locally appropriate, climate friendly, and reflective roofing materials to reduce heat exposure, along with installing shaded pavilions and benches in community spaces and training local members of the community through workshops. As Table 3 summarizes, the prospective benefits of these interventions extend beyond enhanced indoor comfort and safety to improved public health, reduction of the urban heat-island affect, and the advancement of SRM basic science alongside global applications for agriculture and freshwater conservation. This finding highlights that even interventions as specific as those targeting albedo and heat at the level of a single building can generate a multitude of other co-benefits well beyond Freetown or even West Africa. Respondents even articulated a bold vision where MEER technology becomes deployed at scale as the "apex of climate interventions" to lower global temperatures consistently and perpetually.

Table 3: The multi-scalar benefits and challenges facing MEER in Freetown, Sierra Leone

	Prospective benefits	**Perceived challenges**
Local and household level	● Enhanced indoor comfort ● Reduction of energy bills ● Extended roof life	● Corruption ● Theft ● Poverty
Community and city level	● Reduction of urban heat-island effect ● Training and skills development ● Enhanced public health	● Possible negative impacts on local environment ● Lack of local capacity, ignorance about extreme heat among policymakers ● Unable to provide resilience to all climate hazards
Global level	● Advancement of science on solar radiation modification and surface reflection technology ● Applications for agriculture, freshwater conservation, and forestry ● Sustained global temperature reductions	● Stigma against research ● Lack of population level experimental data ● Land constraints to global deployment

Nevertheless, Table 3 also reveals the potency of challenges facing MEER, including ever-present patterns of corruption and ubiquitous poverty, lack of understanding among policymakers, and an emergent stigma against any form of SRM research and deployment, even one as benign as reflective mirrors. This serves as a stark reminder that climate interventions, even when done for free with trusted community intermediaries, are incredibly difficult to implement at the sheer scale of slum, yet alone an entire city. It may be that the true legacy of MEER will not be developing Freetown into a model climate resilient city but rather serving as a beacon for innovative research on direct cooling, helping destigmatize SRM in global climate science and policy discussions. Or, failing that, an important case study from the Global South with richly salient lessons for other cities around the world seeking to adapt to extreme heat.

References

Adegun, Olumuyiwa Bayode, and Hezekiah Adedayo Ayoola. "Between the rich and poor: Exposure and adaptation to heat stress across two urban neighbourhoods in Nigeria." *Environment, Development and Sustainability* 24, no. 10 (2022): 11953-11968.

Allen, A, Osuteye, E, Koroma, B and Lambert, R (2020). "Unlocking urban risk trajectories in Freetown's informal settlements". In UN Habitat (ed.), *Breaking Cycles of Risk Accumulation in African Cities*. Nairobi: United Nations Human Settlements Programme (UN-Habitat).

Atlantic Council. 2023. *Hot Cities, Chilled Economies: Freetown, Sierra Leone*. Available at https://onebillionresilient.org/hot-cities-chilled-economies-freetown/
Baiman, Ron, Sev Clarke, Clive Elsworth, Leslie Field, Michael MacCracken, John Macdonald, David Mitchell, Franz Dietrich Oeste, Suzanne Reed, Stephen Salter, Herb Simmens, Ye Tao, Robert Tulip, Addressing the urgent need for direct climate cooling: Rationale and options, *Oxford Open Climate Change*, Volume 4, Issue 1, 2024, kgae014.
Bangura, Kabba Santigie, Kenneth Lynch, and James Anthony Binns. "Coping with the impacts of weather changes in rural Sierra Leone." *International Journal of Sustainable Development & World Ecology* 20.1 (2013): 20-31.
de Dear, Richard J., Takashi Akimoto, Edward A. Arens, Gail Brager, Christhina Candido, K. W. D. Cheong, B. Li et al. "Progress in thermal comfort research over the last twenty years." *Indoor air* 23, no. 6 (2013): 442-461.
Dinneen, James. Reflective film could cool a city, *New Scientist*, Volume 258, Issue 3442, 2023, Page 11.
Djongyang, Noël, René Tchinda, and Donatien Njomo. "Thermal comfort: A review paper." *Renewable and sustainable energy reviews* 14, no. 9 (2010): 2626-2640.
Feinberg, A. (2024). Annual Solar Geoengineering: Mitigating Yearly Global Warming Increases. *Climate*, *12*(2), 26.
Freetown City Council. *Environmental assessment and evaluation of natural disaster risk and mitigation in Freetown*. 2017.
Gabbe, C. J., Pierce, G., Petermann, E., & Marecek, A. (2024). Why and how do cities plan for extreme heat?. *Journal of Planning Education and Research*, *44*(3), 1316-1330.
Harding, A, G.A. Vecchi, W. Yang, D.W. Keith. 2024. Impact of solar geoengineering on temperature-attributable mortality, *Proc. Natl. Acad. Sci. U.S.A.* 121 (52) e2401801121.
Jay, O., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., ... & Ebi, K. L. (2021). Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *The Lancet*, *398*(10301), 709-724.
Kunda, Joshua Jonah, Simon N. Gosling, and Giles M. Foody. "The effects of extreme heat on human health in tropical africa." *International Journal of Biometeorology* 68.6 (2024): 1015-1033.
Lahai, Morrison. 2024. "Exploring the Link Between Climate Change and Farming in Rural and Peri-Urban Communities in Sierra Leone." *Queios* 14: 3.
Lambert, Rita and Hofmann, Pascale (Eds). (2021) *Transformative strategies for a just Freetown*. The Bartlett Development Planning Unit, University College London: London, UK.
Laue, F., Adegun, O. B., & Ley, A. (2022). Heat stress adaptation within informal, low-income urban settlements in Africa. *Sustainability*, 14(13), 8182.
Luber, G., & McGeehin, M. (2008). Climate change and extreme heat events. *American journal of preventive medicine*, *35*(5), 429-435.
Lynch, Kenneth, Etienne Nel, and Tony Binns. "'Transforming Freetown': Dilemmas of planning and development in a West African City." *Cities* 101 (2020): 102694.
Macarthy, Joseph Mustapha. *Integrating climate change considerations in planning for urban development in Sierra Leone: the case of Freetown*. Diss. Newcastle University, 2012.
Macarthy, JM et al. (2024). "Freetown: City report". *ACRC Working Paper 2024-16*.
Manchester: African Cities Research Consortium, The University of Manchester.
Available online: www.african-cities.org
McLeod, Kathy Baughman. 2021. *Building heat resilience in Freetown, Sierra Leone*. October 18. Available at https://cdkn.org/story/feature-building-heat-resilience-in-freetown-sierra-leone.
McSweeney, C., New, M. and Lizcano, G. (2008). *UNDP Climate Change Country Profiles, Sierra Leone*.
Mukhopadhyay, Barun, Charles A. Weitz, Ketaki Das, Indoor heat conditions measured in urban slum and rural village housing in West Bengal, India, *Building and Environment*, Volume 191, 2021, 107567
Mustafa, Elhadi K., Hazem T. Abd El-Hamid, and Musa Tarawally. "Spatial and temporal monitoring of drought based on land surface temperature, Freetown City, Sierra Leone, West Africa." *Arabian Journal of Geosciences* 14.11 (2021): 1013.
Oladele, Oladimeji Idowu, and Amara Augustine. "Determinants of Climate Change Awareness and the Incidence Across Farming Systems and Agroecological Zones in Sierra Leone." *Journal of Agribusiness and Rural Development* 72.2 (2024): 181-198.
Pasquini, L., van Aardenne, L., Godsmark, C. N., Lee, J., & Jack, C. (2020). Emerging climate change-related public health challenges in Africa: A case study of the heat-health vulnerability of informal settlement residents in Dar es Salaam, Tanzania. *Science of the total environment*, *747*, 141355.
Rahimi, J., Mutua, J. Y., Notenbaert, A. M., Dieng, D., & Butterbach-Bahl, K. (2020). Will dairy cattle production in West Africa be challenged by heat stress in the future?. *Climatic Change*, *161*(4), 665-685.

Rohat, Guillaume, Johannes Flacke, Alessandro Dosio, Hy Dao, and Martin Van Maarseveen. "Projections of human exposure to dangerous heat in African cities under multiple socioeconomic and climate scenarios." *Earth's Future* 7, no. 5 (2019): 528-546.
Scott, A.A., Misiani, H., Okoth, J., Jordan, A., Gohlke, J., Ouma, G., Arrighi, J., Zaitchik, B.F., Jjemba, E., Verjee, S. and Waugh, D.W., 2017. Temperature and heat in informal settlements in Nairobi. *PloS one*, *12*(11), p.e0187300.
Sesay, Abdul Rahman, and Sanpha Kallon. "Livestock farmers' perception, perceived impacts, and adaptations to climate change in Koinadugu district, Sierra Leone." *Journal of Applied and Advanced Research* 7 (2022): 25-34.
Sesay, Abdul Rahman, and Sanpha Kallon. "Analysis of backyard poultry farmers' awareness, perceptions, and adaptability to climate change in Tonkolili District, Sierra Leone." *Asian Journal of Advances in Agricultural Research* 19.1 (2022): 6-17.
Sustainable Energy For All. 2021. *Sierra Leone: Closing the energy access gap with mini-grids*. May 11. Available at https://www.seforall.org/news/sierra-leone-closing-the-energy-access-gap-with-mini-grids.
Stone, Brian, Jeremy J. Hess, and Howard Frumkin. "Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities?." *Environmental health perspectives* 118, no. 10 (2010): 1425-1428.
Sylla, Mouhamadou Bamba, et al. "Projected heat stress under 1.5 C and 2 C global warming scenarios creates unprecedented discomfort for humans in West Africa." *Earth's Future* 6.7 (2018): 1029-1044.
Tao, Y. (2019a). Mirrors for Earth's Energy Rebalancing: Resource-driven engineering leveraging Earth's chemistries to immediately offer remediation. *Bulletin of the American Physical Society*, *64*.
Tao, Ye. 2019b. *Mirrors for Earth's Energy Rebalacing (MEER:ReflEction): Resource-driven engineering leveraging Earth's chemistries to immediately offer remediation*. Rowland Institute, Harvard University, Cambridge MA, USA
Tarawally, Musa, et al. "Comparative analysis of responses of land surface temperature to long-term land use/cover changes between a coastal and Inland City: A case of Freetown and Bo Town in Sierra Leone." *Remote Sensing* 10.1 (2018): 112.
Turay, Bashiru. "Assessing the adaptive capacity of slum households to flooding in the coastline of Portee and Rokupa, Freetown, Sierra Leone." *Climate* 10.11 (2022): 181.
Van Assen, Daniël. *Comparative policy analysis of delta cities Rotterdam, New Orleans and Freetown: Justice in climate change mitigation and adaptation plans*. PhD Dissertation. 2022.
Van de Walle, Jonas, Oscar Brousse, Lien Arnalsteen, Chloe Brimicombe, Disan Byarugaba, Matthias Demuzere, Eddie Jjemba et al. "Lack of vegetation exacerbates exposure to dangerous heat in dense settlements in a tropical African city." *Environmental Research Letters* 17, no. 2 (2022): 024004.World Bank. (2018). *Freetown: Options for Growth and Resilience*. World Bank, Washington, DC. World Bank. https://openknowledge.worldbank.org/handle/10986/31286