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# Double Exposure

## Analyzing Bonaire's Energy Transition and Heat Vulnerability with Earth Observation Data


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## Background

Small Island Developing States (SIDS) face high energy costs due to geographic isolation. Bonaire shares these challenges and has embarked on an ambitious goal to reach 80% renewable penetration by 2030. Along with this goal, Bonaireans are at increased risk of heat stress due to climate change. The intersection of the energy transition and risk of heat stress raises an interesting equity question: are the residents most exposed to extreme heat able to access cheap solar, or are the benefits concentrated among those who can afford to live in naturally cooler areas?

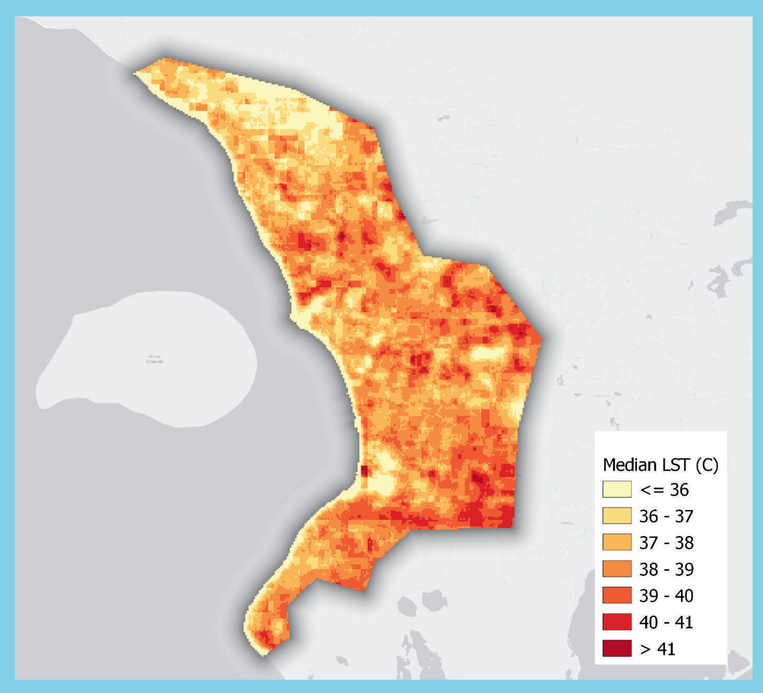

## Research Question

How does rooftop solar adoption instersect with heat vulnerability in Kralendijk's built environment?

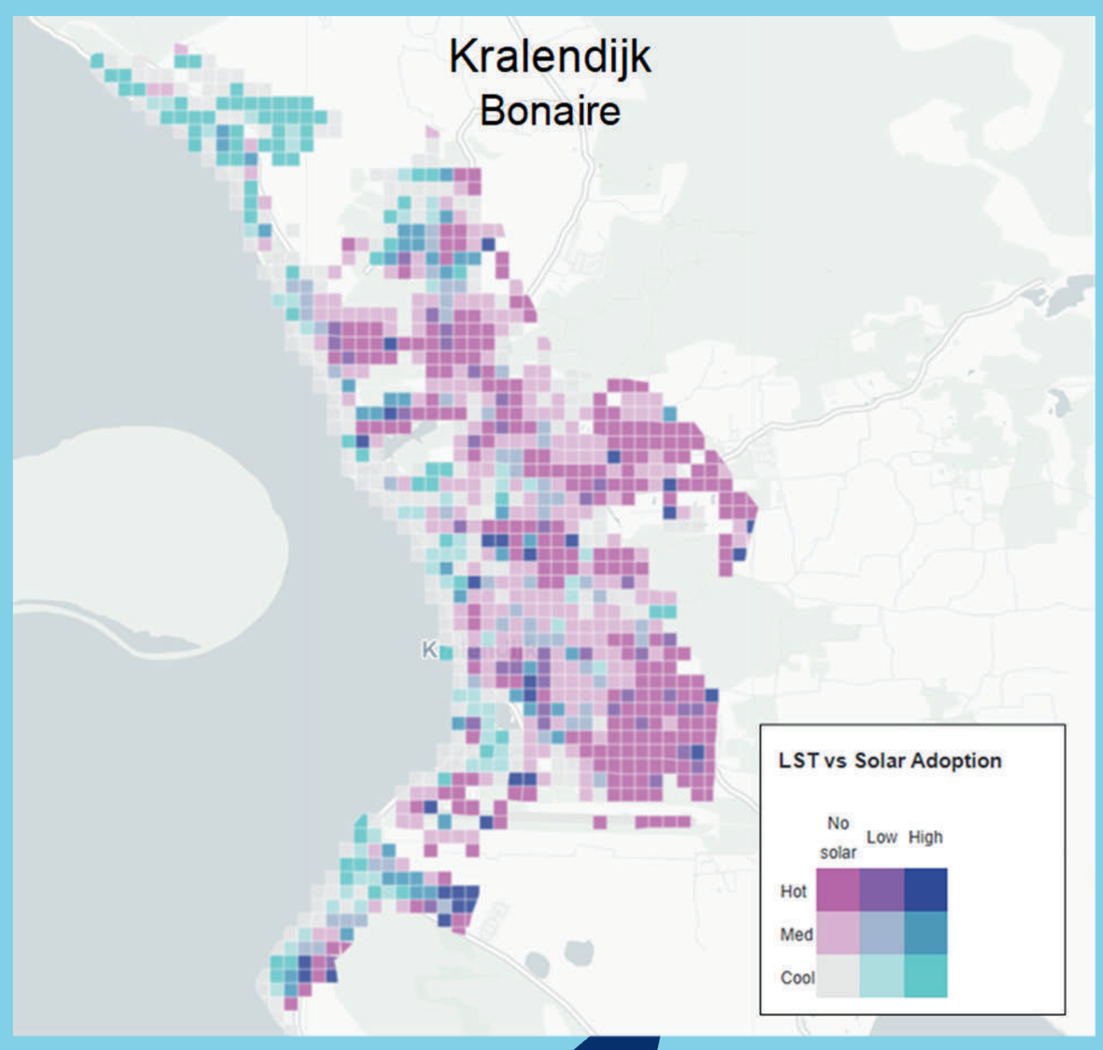
## Methods

Rooftop solar detection with DeepLabv3+ semantic segmentation algorithm transfer-trained on rooftop solar installations in Kralendijk, Bonaire using Pleiades-Neo 30cm data

Land surface temperature aggregation from LANDSAT 8 & 9 in Google Earth Engine




Spatial analysis using 150m x150m gridded cells across Kralendijk




## Conclusions

Residents living in hotter areas of Kralendijk are much less likely to adopt rooftop solar than those in cooler areas. A 1° C increase in LST is associated with -7.5% likelihood of solar adoption (baseline is 30.8%).

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# Marine Cloud & Sky Brightening (MCB/MSB) at Bonaire

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## Coral Reefs of Bonaire

Coral reefs have a diverse range of functions and are an important factor for the wellbeing of the inhabitants of Bonaire:

- they offer coastal protection by decreasing incoming wave intensity
- they serve as nursery habitats for commercial fish species
- they are vital for the tourism industry on the island [1]

Between 1998 and 2018, **more than 90 %** of the coral reefs listed in global World Heritage sites have been **bleached or killed by heatwaves** [2]. Climate projections indicate that if global warming exceeds 2°C by 2100, the Caribbean region could experience widespread coral bleaching events nearly every year [1][3].

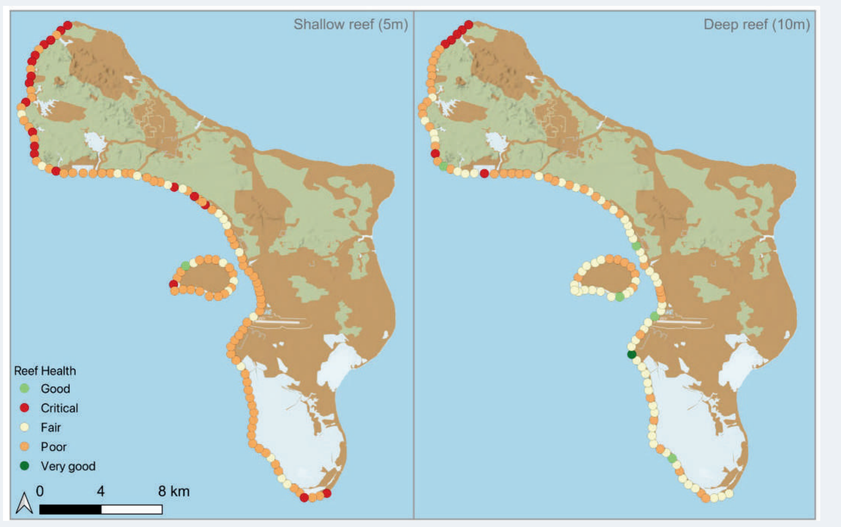


Figure 1: Reef Health index for the Leeward side of Bonaire.

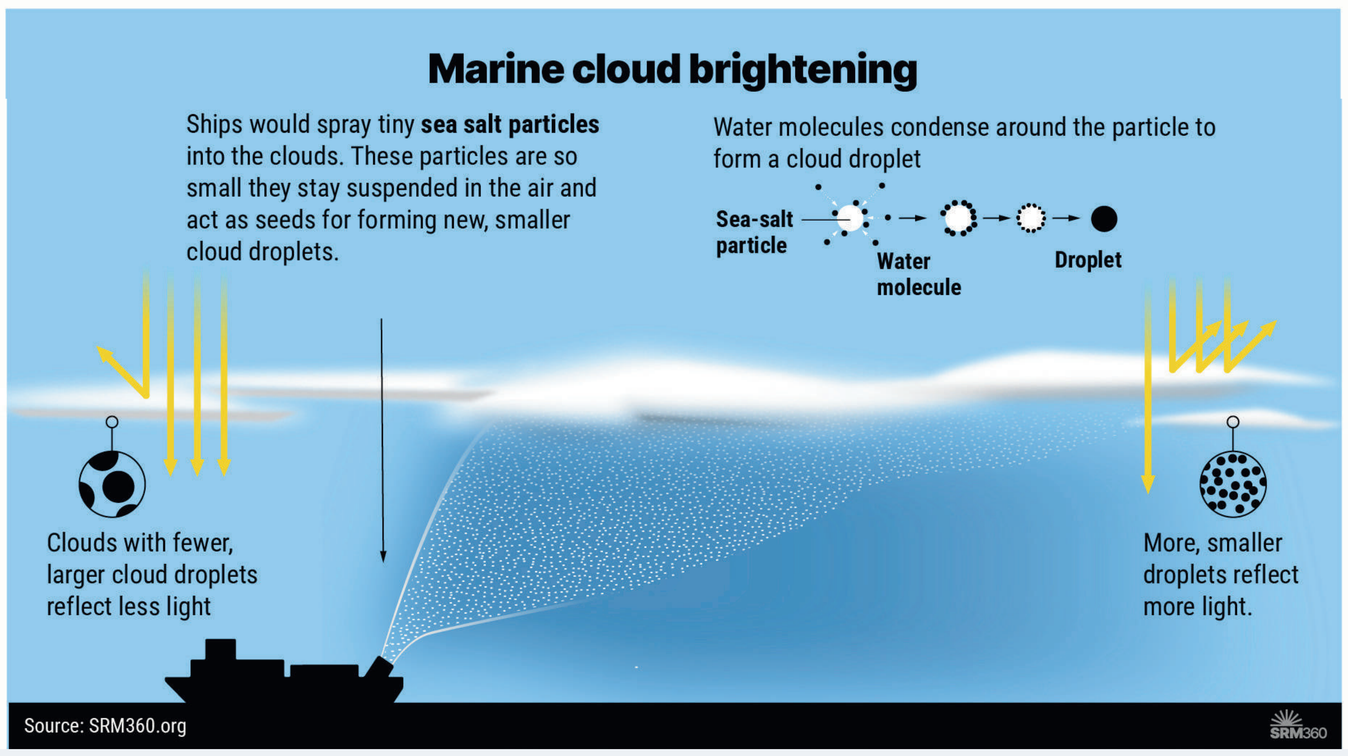


Figure 2: Working principle of Marine Cloud Brightening.

## Marine Cloud Brightening

MCB is a solar radiation modification (SRM) strategy which could provide **local cooling during marine heatwaves**, reducing the risk of coral bleaching.

Water containing sea-salt particles is sprayed into the air, and the salt particles are taken up to the cloud base by convective air streams. Their presence leads to a higher droplet concentration in the cloud, enhancing the cloud brightness (Figure 2). **Brighter clouds reflect more sunlight** and thus reduce the radiation reaching the underlying surface, **creating a local cooling effect** [4].

The MCB principle has been unintentionally proven by shipping tracks: increased cloud brightness following shipping routes is visible on satellite images (Figure 3).

## Marine Sky Brightening

MSB is a related SRM strategy which is still relatively unexplored. It aims to increase the reflectance over the oceans with small haze droplets directly scattering the incoming radiation. The sea-salt particles are sprayed but never reach the cloud base, they remain as a **misting over the ocean surface** to create a local cooling effect [4] (Figure 4).

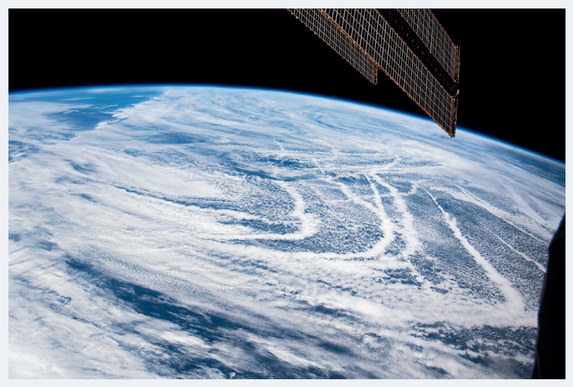

Figure 3: Ship tracks show the localised effect of aerosols on cloud formation.

Figure 4: Marine Sky Brightening in Australia at the Great Barrier Reef.

## Research Method

- The climatology of Bonaire is studied using ERA5 reanalysis data from the Copernicus climate data store.
- Representative heatwave events are selected as case studies for Large Eddy Simulations (LES).
- Different aerosol spraying strategies are tested in the LES to find the most optimal spraying technology.

This research should provide insights that can be used in the development of an experimental plan for a field trial.

## Early Results

Early results indicate that the low marine clouds above Bonaire are not suitable for MCB, while specific heatwave events show potential for MSB implementation. The rest of this study should provide more insight in the suitability of Bonaire for MCB/MSB. This study is ongoing and planned to be completed in December.

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Sources:
[1]: van Beukeringen et al, 2022
[2]: Sovacool et al, 2023
[3]: Hoegh-Guldberg et al, 2017
[4]: Feingold et al, 2024

Figures are taken from:
Figure 1: van Beukering et al, 2022
Figure 2: SRM360, 2024
Figure 3: NASA, 2019
Figure 4: Adam Ferguson, 2025

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# The Limits of Looking: Earth Observation Between Technical Ceiling and Governance Gap

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(Erasmus University of Rotterdam)

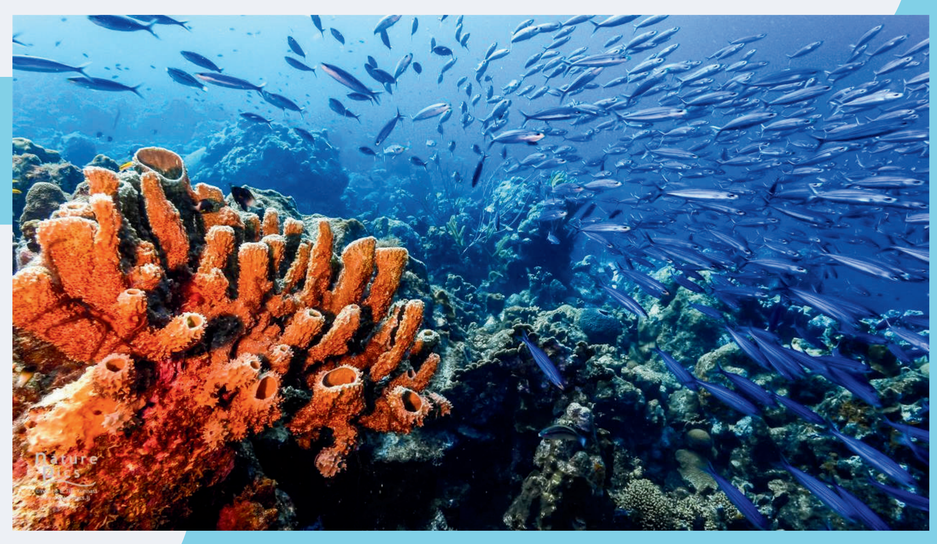
**30%**

Bonaire's coral cover today, down from 62% in the early 1980s

*Tourism generates up to 70% of GDP on the ABC Islands, and the reef itself is the product being sold. Satellite data can already monitor these conditions and could inform how operators respond.*

## Introduction

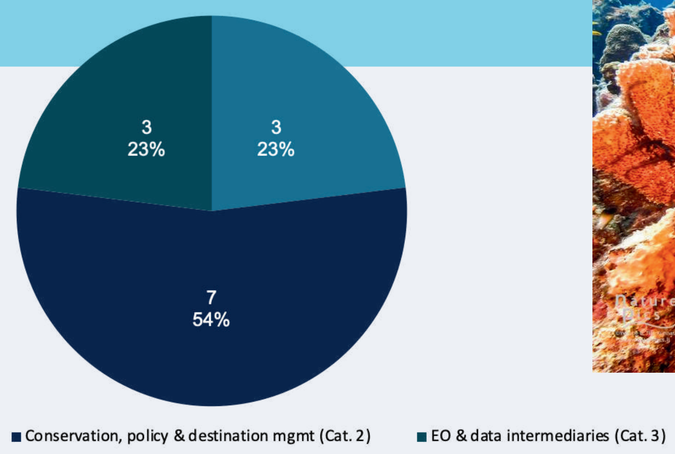
Tourism operators in the ABC islands (Aruba, Bonaire, Curaçao) sell marine ecosystem quality as their primary commercial asset. Earth Observation systems can already monitor many of the coastal and marine risks threatening that asset. Yet satellite-derived risk indicators do not reach tourism operators' operational or investment decisions. This thesis maps why this integration fails across twelve interviews spanning tourism operators, conservation practitioners, and EO specialists, identifies where in the decision process integration could work, and explains what structural conditions would need to change.



## Methodology

Semi structured interviews | 13 interviewees | 3 Islands

Interviewee categories
1. Tourism operators
2. Conservation, policy & destination management
3. EO & data intermediaries




## Results

### I. Aware, but it Changes Nothing

*Gioia Dimension: Risk Awareness Without Decision Relevance*

- Ecosystem degradation is described as severe by all stakeholders, yet treated as background
- Operators run on booking schedules, not environmental data, calling this division of labour natural
  - Example: one operator committed €120,000 to infrastructure with no local sea level data
- Direct experience and personal judgement override formal data, even among conservation practitioners

### II. The Data Doesn't Travel Well

*Gioia Dimension: Technical & Translational Usability Barriers*

- Optical limits mean living coral, dead coral, and algae are often indistinguishable from space
- Producers get no feedback when products fail, so inaccurate outputs are never corrected
- Research and ecological data sit behind institutional walls that practitioners cannot access
- Small island budgets and staffing cannot sustain in house EO capacity or expertise

### III. Governance as Barrier and Pathway

*Gioia Dimension: Structural Conditions as Barrier and Pathway*

- Political cycles and unenforceable guidelines mean environmental rules rarely survive a change in government
- Tourism revenue mostly leaves the islands, limiting local incentive and capacity to act
- A regulatory mandate and regional coordination are the conditions most likely to enable integration

## Discussion & Recommendations

Across all three dimensions, the absence of EO integration is not explained by a lack of awareness or operator interest. Risk awareness exists without translating into decisions, and the institutional layer that would convert awareness into action does not yet exist. Some EO products are also genuinely constrained by sensor limits in the optically complex coastal settings tourism depends on, a technical ceiling that governance alone cannot remove. The recurring pattern is that integration depends on governance conditions wherever the underlying technical capability already exists, but no institutional fix can substitute for what satellites cannot reliably measure.

### Recommendations

| Tourism Operators | Conservation Organisations | Destination Management Organisations | Government Actors | EO & data intermediaries |
|---|---|---|---|---|
| Participate in reef observation logging when conservation organisations or government bodies request it | Initiate reef observation logging requests to dive schools and tourism operators | Connect environmental KPI frameworks to EO data systems via site-specific products | Build a regional EO procurement structure treating the three islands as one buyer | Design products backwards from operator needs, not from available data |
| Request EO exposure projections before major coastal infrastructure investments to inform decisions | Standardise logging around the variables EO products need for in-situ validation | Host producer-user engagement to define product requirements and test outputs | Create a public platform for government held ecological data | Build a feedback mechanism so inaccurate outputs get corrected, not abandoned |
| Integrate SST threshold alerts into dive scheduling and guest communication once available | Advocate for legal sharing of protected area research and a public data platform | | Tie monitoring compliance to existing permits, licences, and certifications | Process EO outputs for all three islands together to cut per-island cost |
| | | | | Treat the dive school network as a primary in-situ validation data source |

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Sources:
[1] Relles et al., 2018 (coral cover decline, 62% to 30%)
[2] World Travel and Tourism Council, 2026 (tourism share of GDP)
[3] Hedley et al., 2016 (EO limits in coral classification)
[4] Cash et al., 2003 (salience, credibility, legitimacy)
[5] O'Brien & Leichenko, 2000 (double exposure)
[6] Daft & Lengel, 1986 (organisational information processing theory)
[7] Gioia et al., 2013 (Gioia methodology)

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# Multispectral remote sensing of coastal ecosystems and sea level rise in Bonaire and Aruba

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Understanding coastal dynamics and related risks is crucial for the Dutch Caribbean, as they are characterized by small island systems with a strong concentration of population and infrastructure along the coast, and a high vulnerability to climate change impacts such as sea-level rise, increased storm intensity, and coastal erosion. In response, this research is to assess the reliability and robustness of remote sensing-based coastal analysis across coastline configuration of Aruba and Bonaire between 2021 and 2026.

## Methodology & Preliminary Findings

Combining optical and radar data is essential to capture both state and driver within a vulnerability assessment around the coastal typology of Aruba and Bonaire

Through spectral indices of high resolution observations, spatial indicators could be developed to measure coastal change, natural buffers, built-up intensity, and external exposure

Driving variables for a higher vulnerability from coastal change are hypothesized to include built-up intensity, vegetation buffers, and external exposure conditions

Preliminary findings indicate EO to have the capacity to detect coastlines and buildings, providing the opportunity to conduct localised risk analyses

However, optical observations at the desired 30cm resolution are not frequently available for Aruba and Bonaire, limiting year to year intercomparison

Furthermore, only L1 data (top of atmoasphere) are available through the NLSA data portal, creating an additional challenge to work with the data.

*The presented results are preliminary as the study was during publication of this white-paper at its midterm phase. The final results will be provided on the LDE Thesis Labs website and in the thesis-repository of TU Delft when completed.*

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# From Earth Observation Data to Flood Risk Management Services

## Entrepreneurial Opportunities on Bonaire

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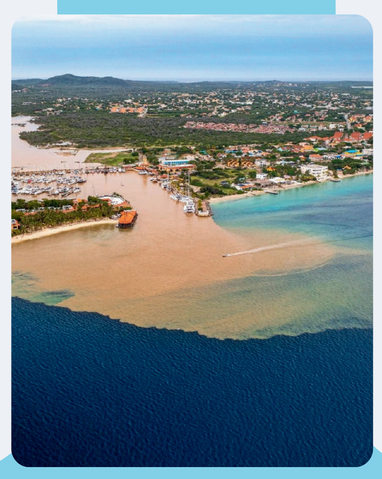
## Introduction

Climate change is making extreme rainfall more frequent, and small islands like Bonaire are highly exposed. Homes, infrastructure, and the economy sit in low-lying coastal areas, while local data and capacity are limited. The November 2022 floods made this visible. In January 2026 a court ruled the Netherlands had not done enough to protect the island. Earth Observation (EO) satellite data can help monitor and predict floods, and is openly available for the Dutch Caribbean. The problem is that raw data is not directly usable.

## Research Questions

Main: How can EO data be translated into entrepreneurial flood risk management services on Bonaire?

1. What do potential customers need from flood risk management services on Bonaire?
2. Which EO data and service features best address those needs?
3. What are the opportunities and challenges for entrepreneurs developing these services?



## Methodology

- Stakeholder analysis using a power-interest grid to map actors by influence and interest
- 21 semi-structured interviews with stakeholders on Bonaire and in the Netherlands: government, knowledge institutions, nature organisations, the private sector, and EO companies.
- Three-week field visit to Bonaire (10 April–1 May 2026), including the EU Satellite Conference, supported recruitment and local context.
- Interviews designed using The Mom Test.
- Three-phase thematic coding in ATLAS.ti.

## Results & Recommendations

The findings follow the value chain.

**Customer needs (RQ1)**

1. Restoring water storage through dams and saliñas
2. Better drainage
3. A faster and more reliable early warning system
4. More awareness of how to use EO

**Suitable EO data and features (RQ2)**

No new satellite data is needed, only a service that turns existing data into usable products:

- Prevention: combine elevation, water flows, and infrastructure in one tool; spot dams and drainage needing restoration; flood risk models for planning
- Response: early warning systems
- Recovery: damage assessment, still an underused opening

**Opportunities and challenges (RQ3)**

The service provider role is the missing link in the value chain. Three things keep it empty:

- Awareness of EO is low across most user groups
- The obstacle is financial, not technical. Services lose funding once a pilot ends
- Adoption depends on trust. The most interested actors have the least power

**Recommendations**

**For entrepreneurs**: serve several islands, not Bonaire alone, with early public funding and a local champion
**For government: structural funding:** clear maintenance responsibility, and flood risk in the zoning plan

## Value Chain

**Data providers**

*Actors responsible for collecting and supplying EO data*

**Processed data**

**Service providers**

*Actors responsible for translating data into information services*

**Products & Services**

**Customers**

*Actors who use services for decision-making and implementation*

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# Buffer Zones' Impact on Protected Area Boundary Rigidity

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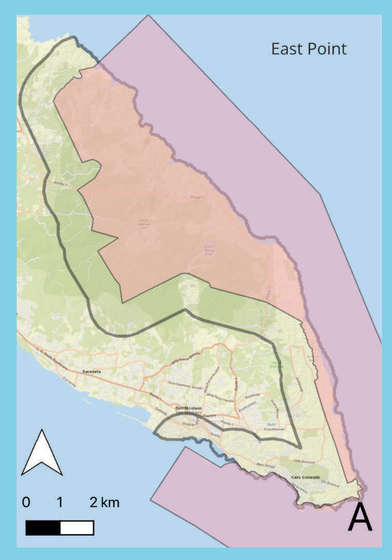
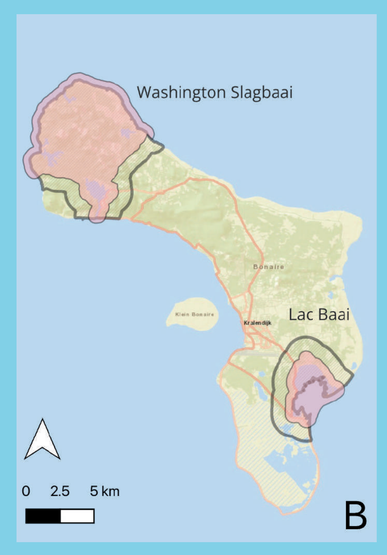
Supervisors: Michiel Veldhuis (CML) & Antonella Maiello (FGGA)

## Introduction

Ramsar sites are internationally protected wetlands; climate change threatens the nature they preserve [1]. This thesis measures the rigidity of boundaries of Ramsar sites on Aruba and Bonaire to identify the influence of buffer zones. 'Boundary rigidity' defines the gradient at the borders of protected areas, identifying areas of 'hardness' and 'softness' where protected areas (PAs) abut human-dominated areas abruptly or occupy a shared transition space, respectively [2]. Three sites, East Point (Figure A), Washington Slagbaai (Figure B), and Lac Baai (Figure B) are assessed. Further, interviews investigate the broader use of remote sensing technologies and data in the Dutch Caribbean.




## Methods

Two quantitative ecological methods were deployed to analyze rigidity by identifying boudaries and characterizing the intactness of three zones along the PA gradient: the border of the core PA, the border of the 500-m buffer zone, and the border of the 1-km outer transition area. A qualitative method, interviews, identified the context of remote sensing use in the Dutch Caribbean, including opportunities and challenges for nature monitoring.

**Edge detection**

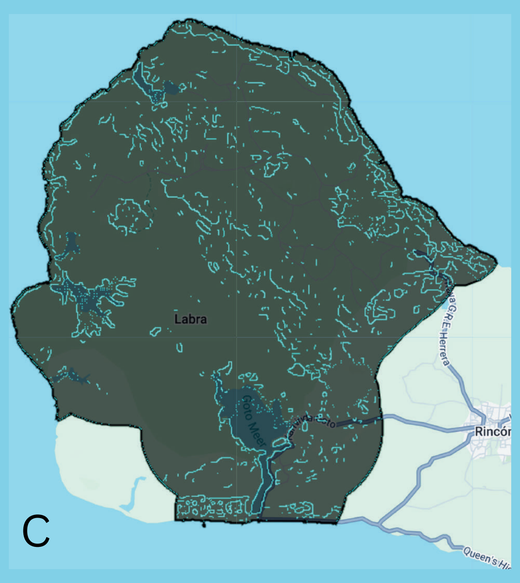
- Identify where in the site hard boundaries are present
- Test for temporal and seasonal variation
- 2013-2026; 30-m Landsat 8

**Woody coverage & lacunarity**

- Calculate the vegetation coverage and clustering within PA core, buffer zone (BZ), and outer transition area (OTA)
- 2025; 30-cm Pleiades-Neo

**Interviews**

- Interview local and regional stakeholders to identify how remote sensing is used in nature monitoring




## Results

**Edge detection**

- Hard boundaries form around human-built and natural features (Figure C)
- Boundaries remain relatively stable both temporally and seasonally

**Woody coverage & lacunarity**

| *Site* | Core | | BZ | | OTA | |
|---|---|---|---|---|---|---|
| *Washington Slagbaai* | 74.98% | **.7600** | 81.01% | **.6822** | 72.99% | **.7211** |
| *Lac Baai* | X | **X** | 21.77% | **.8666** | 23.79% | **.8586** |
| *East Point* | 27.14% | **.8546** | X | **X** | 37.89% | **.8462** |

**Interviews**

- Nature-focused organizations in the Dutch Caribbean make limited use of EO, or data offered by the NLSA
- A lack of capacity, knowledge, and financial resources limit the use of EO for nature purposes

## Analysis

Human-defined PA borders remain as "paper borders." Rather than legal borders, the transboundary habitats and geomorphology of the sites are more indicative of canny edge-detected hard boundaries. This indicates that **these sites are examples of soft boundaries**, in that the edges defined are not aligned with sharp changes in vegetation at their legal borders, instead being characterized by a gradual transition.

A Dutch Caribbean **'Digital Earth' is a welcome idea, though faces similar challenges** to current EO use. Physical infrastucture is missing, and without it, digital EO skills will remain underused. Importantly, EO programs must be co-created and co-managed with Dutch Caribbean nature organizations to ensure relevancy. Further, open-source data and replicable EO methods can boost nature monitoring in the Dutch Caribbean.

## Conclusions

1. Ramsar sites exhibit characteristics of a soft boundaries, forming gradual transitions across borders. Buffer zones do not appear to have had an impact on boundary rigidity, but are important safeguards against future pressures.
2. Remote sensing is not widely used by nature organizations in the Dutch Caribbean, though there is abundant potential for greater adoption given the data and tools exist. Capacity and financial resources are major barriers.

## Future Work

- **Increase co-creation** with local and regional stakeholders or risk further "flashy science" that is poorly adapted to Caribbean needs
- **Engage with nonacademic knowledge** sources and expertise, for example via countermapping

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[1] Debrot, A. O.; Henkens, R. J. H. G.; Verweij, P. J. F. M.; van den Burg, M. P.; Meesters, E. H. State of Nature Report for the Caribbean Netherlands, 2024: A Second 6-Year Assessment of the Conservation State, Threats and Management Implications for Habitats and Species in the Caribbean Netherlands; Wageningen Marine Research, 2025.
[2] Veldhuis, M. P.; Ritchie, M. E.; Ogutu, J. O.; Morrison, T. A.; Beale, C. M.; Estes, A. B.; Mwakilema, W.; Ojwang, G. O.; Parr, C. L.; Probert, J.; Wargute, P. W.; Hopcraft, J. G. C.; Olff, H. Cross-Boundary Human Impacts Compromise the Serengeti-Mara Ecosystem. Science 2019, 363 (6434), 1424–1428. https://doi.org/10.1126/science.aav0564.

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# Legal Challenges and Governance of the Use of EO data

**Wenzhen Chen**
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## Introduction

- The Dutch Caribbean faces growing sustainability challenges, including climate change, biodiversity loss, coastal degradation, and increasing pressure on fragile island ecosystems. EO data offers the Dutch Caribbean valuable tools for monitoring ecosystems, supporting climate adaptation, and advancing sustainable development. However, the legal and policy environment governing EO data access and use is fragmented, limiting the sustainable use of data and the use of data for sustainable developments. Adopting a doctrinal legal methodology combined with comparative analysis, this research examines how legal fragmentation shapes the sustainable utilisation of EO data and explores governance approaches.

## Research Question

How can legal and governance approaches address the challenges posed by legal fragmentation to the sustainable utilisation of EO data for the Dutch Caribbean?

## Methodology

- Doctrinal legal methodology
- Comparative analysis approach
- Case-study method

| Challenge Area | Key Challenges | Recommendations |
|---|---|---|
| **1. Governance Fragmentation** | • Limited integration of EO data in decision-making<br>• Lack of consistent data standards and sharing practices | **Establish an EO Coordination Framework**<br>Strengthen coordination across local, national and international actors.<br>**Create a Multi-stakeholder Advisory Body**<br>Facilitate cross-sector collaboration and knowledge sharing. |
| **2. Data Access and Licensing Fragmentation** | • Different licensing terms and access conditions<br>• High costs for commercial data<br>• Uncertain long-term data availability | **Promote Public-Interest Data Agreements**<br>Negotiate preferred access to commercial data.<br>**Ensure Long-term Data Availability**<br>Adopt data continuity and archiving policies. |
| **3. National Security Regulatory Fragmentation** | • Varying national security regulations and export controls<br>• Restrictions on resolution and sensitive areas<br>• Uncertainty in accessing high-quality data over time | **Advocate for a Sustainability Exception**<br>Promote an "environment and climate" exception.<br>**Build Trusted Data Partnerships**<br>Establish stable data-sharing arrangements.<br>**Prioritize Open EO Data**<br>Maximize open and free EO resources. |

## Conclusions

- This research finds that, from legal perspectives, the challenge for the sustainable utilisation of EO data in the Dutch Caribbean is fragmentation in the legal and policy frameworks governing its access and use. Fragmented governance arrangements, data access regimes, and security-related regulations can limit the contribution of EO data to sustainability governance. To enhance the value of EO data, policymakers should strengthen institutional coordination, improve long-term and equitable data access, and better integrate sustainability objectives into EO governance frameworks.
- Future research could explore how emerging technologies, such as artificial intelligence, may further influence the governance and sustainable utilisation of EO data.

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# Decoding Sargassum's impact on tropical small island tourism

## A case study of Bonaire with SatEO data

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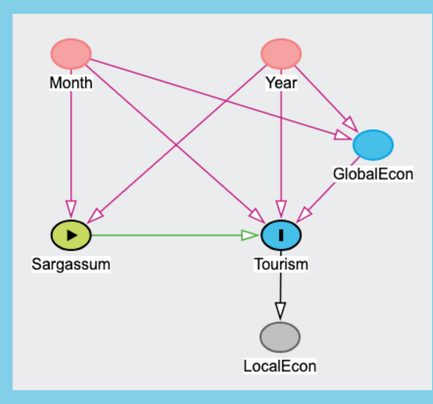
Supervisor: Dr. J. M. T. Roos

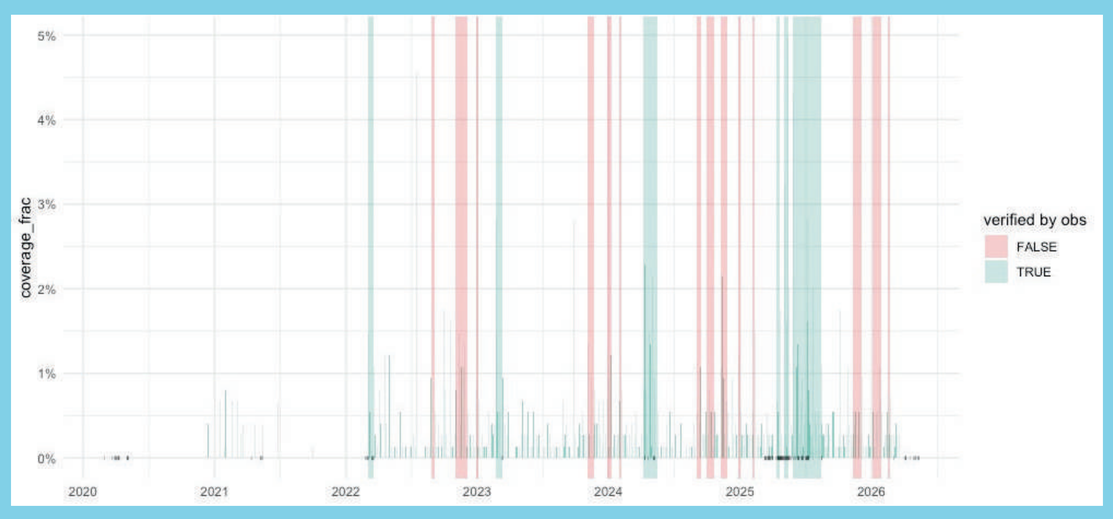
## Introduction

*Sargassum*, a brown algae, has been promoted to excessive growth in recent decades by such environmental change, causing yearly blooms that damage the local economies of the Caribbean islands, especially by inhibiting tourism. The development of high-resolution SatEO technology and the methods for processing SatEO data provide an invaluable opportunity to study Sargassum influx events and their socioeconomic effects across temporal and spatial scales.

## Methods

I first converted raw AFAI geospatial time series data from Sentinel-2 and Landsat observations into a continuous, event-filtered measure of coastal *Sargassum* exposure. I then validated the events using on-ground observation data from a citizen science project. Finally, I regressed tourism statistics drawn from Statistics Netherlands (CBS) to the exposure record with the general model of $g(y_t) = \alpha + \beta \cdot Sargassum_t + \gamma \cdot month(t) + \delta \cdot year(t) + \varepsilon_t$.




## Results

**The coastal *Sargassum* exposure record**

- *Sargassum* is detected in 340 days for Bonaire from 2022 to 2025, constituting 20 events, of which 6 are verified by ground observations.
- Vague seasonality of Sargassum influx is detected during spring and summer.

**Effect of *Sargassum* exposure on tourism**

- No robust causal effect of *Sargassum* influx on tourism is found.
- Positive coefficients and significant effects are artefacts of uncontrolled confounders and outliers.

## Discussion

The citizen science-based, ground-truth observation reports are proven to be an invaluable resource for a better understanding of the *Sargassum* influx events. However, citizen science-based observations should not be used as a substitute or a validation source for SatEO detection because of a major limitation. First, as available citizen science project have minimal information requirements for a report, the scale of the Sargassum observation and whether it is associated with an influx event is hard to assess, resulting in false positives. Second, the volunteer nature of citizen science-based reports caused the report of presence itself to depend on the presence of volunteers, resulting in obscurity between missing data and true false.

The absence of a detectable deterrence effect of *Sargassum* influx on tourism is the study's principal finding. The models and subsequent robust tests demonstrate how outliers change the conclusion of a model. Several limitations are present in the models, inspiring future research with models incorporating additional controls and lag effects. On the other hand, accessibility to Sargassum influx detection before 2020 and tourism data for other islands will greatly expand the current models.

## Managerial Inference

- **For island government and public bodies:** adopt a precautionary approach to deal with the future risk; focus on heavily-impacted locations.
- **For tourism businesses:** marketing opportunities of a *Sargassum*-free destination.
- **For local communities:** investment in clean-up, disposal and habitat protection is justified on public-health and ecosystem grounds alone.
- **For the wider Caribbean and SatEO vcommunity:** the study is a concrete demonstration that Earth observation from publicly funded projects, joined to civil statistics, can answer governance questions for the Dutch Caribbean.

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# Heat & Inequity in Curaçao

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## Introduction

As climate change intensifies, extreme heat poses growing risks in Curaçao. This study links environmental exposure with social vulnerability to reveal spatial heat inequities and support fair, targeted adaptation strategies in small-island contexts.

## Research Questions

**To what extent is the burden of heat in Curaçao distributed inequitably across neighbourhoods?**

1) Where are the hottest land surface temperature (LST) zones located in Curaçao?

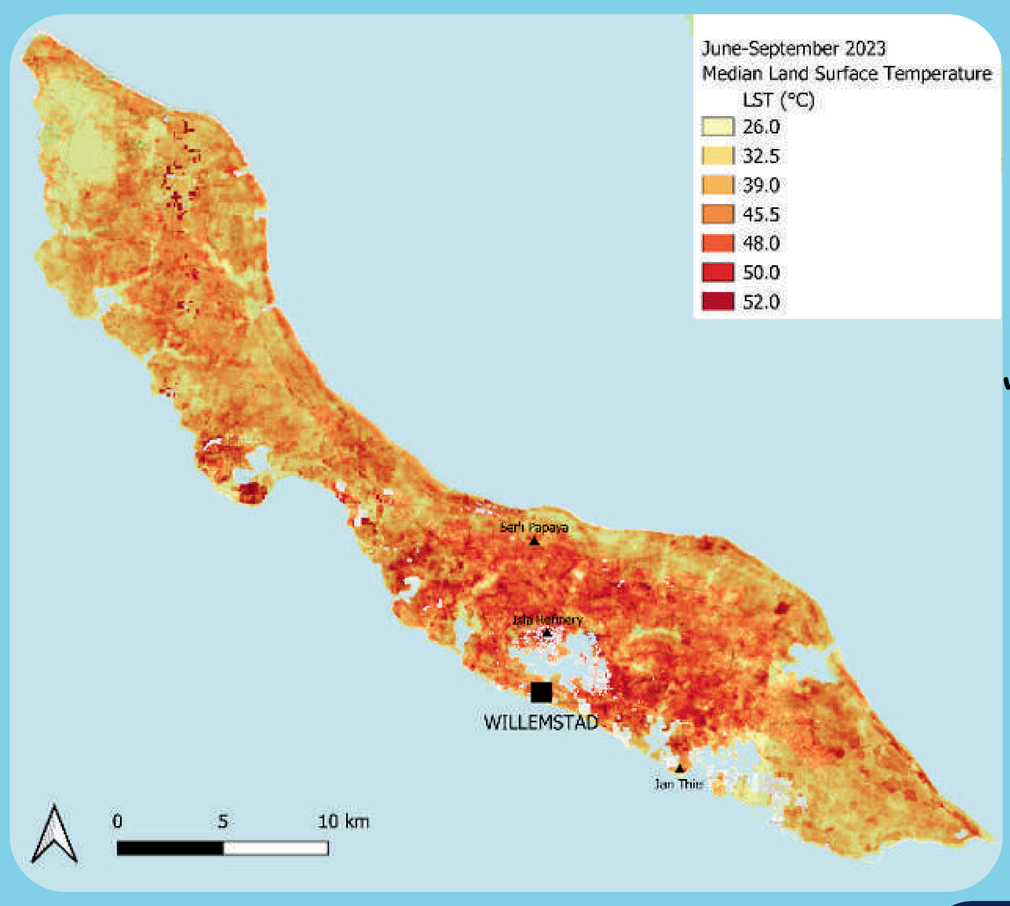
2) Which social groups are most exposed to elevated temperatures?

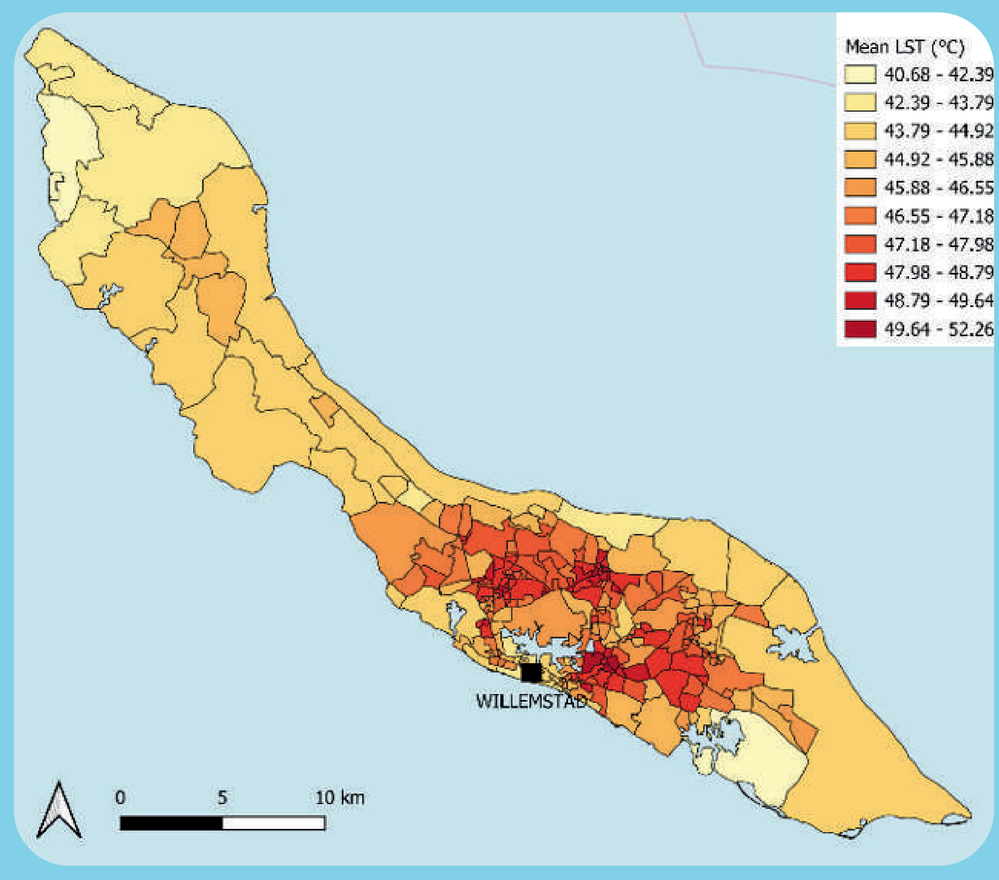
3) Do socially vulnerable neighbourhoods experience disproportionately higher heat burden compared to less vulnerable ones?

## Methodology

- Land surface temperature data extracted from landsat 8 and 9 → water masked, cloud filtered → scenes from June to September 2023 used to make an LST median composite.
- 2023 Census data and neighbourhood map used from Central Bureau of Statistics Curaçao.
- Vulnerability indicators identified through literature, correlation, and mulitcollinearity tests.
- Regression analysis (OLS, SAR, SEM) used to study multivariate relationship with neighbourhood LST.
- Moran's I used to test for spatial autocorrelation.

## Land Surface Temperature Maps of Curaçao




## Conclusions

**Heat burden is concentrated in dense urban areas** → particularly in and around the capital, Willemstad, and peri-urban neighbourhoods.

**Standard vulnerability indicators** used in environmental justice literature **do not consistently predict heat burden in Curaçao** → renter status, income, unemployment, and age show no significant association with LST.

**Native-born residents face compounding exposure** → since many are concentrated in hotter inland and industrial neighbourhoods, consistent with tourism-driven displacement.

Effective heat adaptation policy should **prioritise physically-targeted interventions in areas where thermal burden and demographic vulnerablity intersect**, alongside affordable housing policies to address displacement.

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