How to Advance Earth Observation for the Dutch Caribbean

A multi-disciplinary perspective from a thesis lab of 9 LDE students

LDE Thesis Lab 2025-2026

Universiteit Leiden

TU Delft

Erasmus University Rotterdam

Thesis Labs
Leiden-Delft-Erasmus Universities

This book is published by the joint graduate Thesis Labs program of the Leiden-Delft-Erasmus (LDE) initiative. The collaboration between Leiden University, TU Delft, and Erasmus University Rotterdam is in the form of a strategic alliance, and seeks to contribute towards understanding and solving the major and complex social issues of our time. LDE works with societal partners and seeks to form a basis for further academic and public-private partnerships.

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Foreword

As Director of Space Applications at the Netherlands Space Agency (NLSA), I am proud to introduce this white paper, which showcases the innovative work of ten talented students from Leiden University, Delft University of Technology, and Erasmus University Rotterdam. Their work reflects one of the NLSA's important missions: turning satellite data into practical knowledge and applications that benefit society. Over the past months, they have explored how Earth Observation (EO) can contribute to tackling challenges in the Dutch Caribbean islands of Aruba, Bonaire, Curaçao, Saba, Sint Eustatius, and Sint Maarten. I would like to express my sincere gratitude to the universities for their expert guidance throughout this inspiring process.

The Dutch Caribbean, like many small islands, faces significant threats from climate change, including sea-level rise, saltwater intrusion, extreme weather, and biodiversity loss. In addition, there are also challenges related to civil security, agriculture and more. Addressing these challenges effectively requires a two-way exchange of knowledge and expertise. In the Netherlands, we possess substantial expertise in EO applications and related legal and economic matters, while the Dutch Caribbean bring invaluable local knowledge, cultural context and local priorities. As NLSA, we are committed to contributing to this collaboration by increasing awareness of this work, continue to provide very high resolution satellite data via the national satellite data portal, actively seeking partnerships with local stakeholders and helping connect research, data and users. Together, we can combine our strengths to develop solutions that are both innovative and grounded in the realities of the region.

In this Thesis Lab, students investigated a wide range of topics, demonstrating the versatility of EO applications. Their research spanned societal impact, business opportunities, law and policy, and technical EO applications, covering subjects such as (coastal) ecosystems, heat stress, inequality of opportunities and flood risks.

This white paper highlights the potential of EO and the power of collaboration. It also shows how student research can help bridge the gap between available satellite data and concrete applications that support informed decision-making by communities, governments and organisations in the region. By working together, we can create a sustainable and resilient future for the Dutch Caribbean.

Coco Antonissen
Director Space Applications at
Netherlands Space Agency - NLSA

Netherlands Space Agency

Hello, World. Photo by Reid Wiseman / NASA

Did you know that?

Constraints imposed by fragmented national security regulations on exporting EO data undermines long-term sustainability.

20 Events of Sargassum influx was detected for Bonaire from 2020 to 2025.

Saliñas are shallow salt marshes that flood via channels to the ocean, fluctuating in salinity throughout the year.

Solar panels currently provide 8% of electricity consumed on Bonaire, compared to 17% in the European Netherlands.

Land surface temperatures can average up to 52°C in Curaçao neighbourhoods.

Bonaire could lose 74 of its 86 currently healthy dive sites by 2050 under projected climate scenarios.

Relevance

The Dutch Caribbean (i.e., Aruba, Bonaire, Curacao, Saba, Sint Eustasius and Sint Maarten) are disproportionally affected by climate change related threats, such as sea-level-rise, salt-water-intrusion, severe weather events and biodiversity loss. Natural disturbances, previously considered an integral part of ecosystem dynamics, can now cause irreversible change to the state of ecosystems, and at the same time, negatively impact social and economic systems. Indeed, small island states, including the Dutch Caribbean, are recognized, since the UN Conference on Environment and Development in 1992, as unique territories on basis of their environment and their population.

Adaptation to climate change and variability is thus urgently needed. A key challenge that restricts progress relates to data and local measurement sites. Specifically, comprehensive and comparable observations of essential climate change and biodiversity variables are rare. Furthermore data sources differ in their depth of reporting or utilize different definitions of adaptation. This restricts, both evidence-based policy making and tracking of progress along national and international sustainable development goals.

Earth Observation (from planes and satellites) has the potential for addressing this challenge by providing multiscale information for these SIDS from sensors without being locally operated. Indeed, remote sensing has been presented as a cost-effective method to monitor the plantations of mangroves in Bonaire, create early warning systems and long-term integrated management frameworks. While open-source satellite earth observation provides a means to derive a subset of these essential variables, application of satellite remote sensing is still limited on the Dutch Caribbean, as it still requires a capacity to analyze these satellite images, a legal framework to work in, stakeholders to interact with each other, and a funding stream to support this.

In this thesislab, we define four challenges (societal impact, business opportunities, law and policy and EO applications) for students to explore how earth observation (from the Copernicus data and services, as well as the very high resolution EO data in the NSLA Satellite Data Portal) can be used to aid in the transition towards a more sustainable and resilient Caribbean.

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Key Highlights

The overall finding of research performed within this LDE Thesis Lab is a high potential of Earth Observation for the Dutch Caribbean for hydrological, ecological, climatic and energy-transition applications.

EO for the Dutch Caribbean reveals...

- Habitat transitions at the nature-human interface surrounding Ramsar Sites can be mapped - *Maxime Léger*
- The data exists, but the absence of product translation limits its usability for firms - *Demi Timmers*
- Energy transition inequities in Bonaire, resulting indirectly from their energy transition policy - *Christopher Hastings*
- Tourism operators lack the capital, in-house capacity, and long-term incentive structures to act even when risk is known - *Demi Timmers*
- Intricate relationships between heat stress and disadvantaged groups in Curaçao - *Alyssa Wells*
- Supplementing EO detection on natural phenomenon with ground-truth data increases accuracy. - *Zoey Liu*
- A need for maintained dams and saliñas, improved drainage, and spatial planning to prevent floods - *Kim Bosch*
- Sargassum bloom doesn't have robust effect on Bonaire's tourism, but may induces tourist-movement between the islands. - *Zoey Liu*
- The capacity to detect coastlines and buildings, providing the opportunity to conduct localised risk analyses - *Josephine Winterdal*
- Fragmentation of governance foundations, data access regimes, and security-related regulations constraining integration of EO data - *Wenzhen Chen*

Open Challenges

Capitilizing on the above mentioned potential for earth observation for the Dutch Caribbean is however constrained to several open challenges., that need to be resolved before true impacts can be created.

EO for the Dutch Caribbean requires...

More Co-creation/management with local stakeholders to meet their relevant needs- *Maxime Léger*

Tourism-specific products designed around decision type, not data availability - *Demi Timmers*

Better corroboration with ground-based sensors and local expertise - *Christopher Hastings*

More publicly availability of products. - *Zoey Liu*

More context-specific research - the Dutch Caribbean is very different from places where most remote sensing frameworks are developed - *Alyssa Wells*

A less complicated system to access the data - *Josephine Winterdal*

More in-situ measurements and historical data-sharing. - *Kim Bosch*

More available data, both in spatial and temporal context - *Josephine Winterdal*

A better coordinated governance framework to strengthen institutional cooperation, ensure long-term data accessibility, and enhance regulatory resilience - *Wenzhen Chen*

High resolution atmospheric and oceanic datasets, to accurately describe coastal processes and reanalysis in small-island environments - *Daan Smulders*

Better intermediation at the Governance-level to facilitate firm-level adoption - *Demi Timmers*

Investments in EO training and education - *Kim Bosch*

Individual findings from student researches

Pleiades Neo - True color observation of the South Coast of Aruba, at 10 Jul 2025 15:17

EO for the Tourism Sector

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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.

Findings & Recommendations

Operators handle daily decisions well, but have no equivalent process for investment decisions.

Ecological data often doesn't reach the practitioners responsible for managing it.

Ecological decline elsewhere is redirecting tourists to Bonaire, masking local risk.

Short political cycles and ten-year investor horizons block long-term environmental governance.

Boundary organisations are needed to translate satellite data into investment-level decisions.

Design EO products backwards from operator needs, not forwards from available data.

Clustering the islands into one buyer could make EO services commercially viable.

A regulatory mandate could create demand where commercial incentives alone cannot.

EO integration in Dutch Caribbean tourism is not a technology problem, or a motivation problem. It is a governance architecture problem. The satellite can observe. The decision system cannot yet receive. Closing that gap requires building the institutional infrastructure between orbit and operations.

Rooftop Solar Adoption and Heat Vulnerability in Bonaire

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Bonaire's goal to reach 80% renewable energy penetration by 2030 is ambitious yet achievable with the right policy instruments. A combination of utility-scale installations along with distributed generation (such as rooftop solar) is likely necessary to achieve this goal. Using 30cm Pléiades Neo data collected over Bonaire, this thesis revealed that current policy regarding rooftop solar has resulted in its inequitable adoption with regard to heat exposure. Populations located in areas at the highest risk of heat stress are also less likely to have affordable energy provided by rooftop solar.

Findings & Recommendations

Holding urban form constant, areas of Kralendijk that have not adopted rooftop solar are significantly hotter than areas that have

Grid connectivity and balancing are major factors preventing larger uptake of rooftop solar

Heat vulnerability as measured through land surface temperature shows significant variability across Kralendijk

Populations in poorer neighborhoods are doubly exposed to higher heat exposure as well as higher energy costs

Establish routine EO-based monitoring of rooftop solar adoption and urban heat vulnerability to track progress toward equitable energy transition outcomes

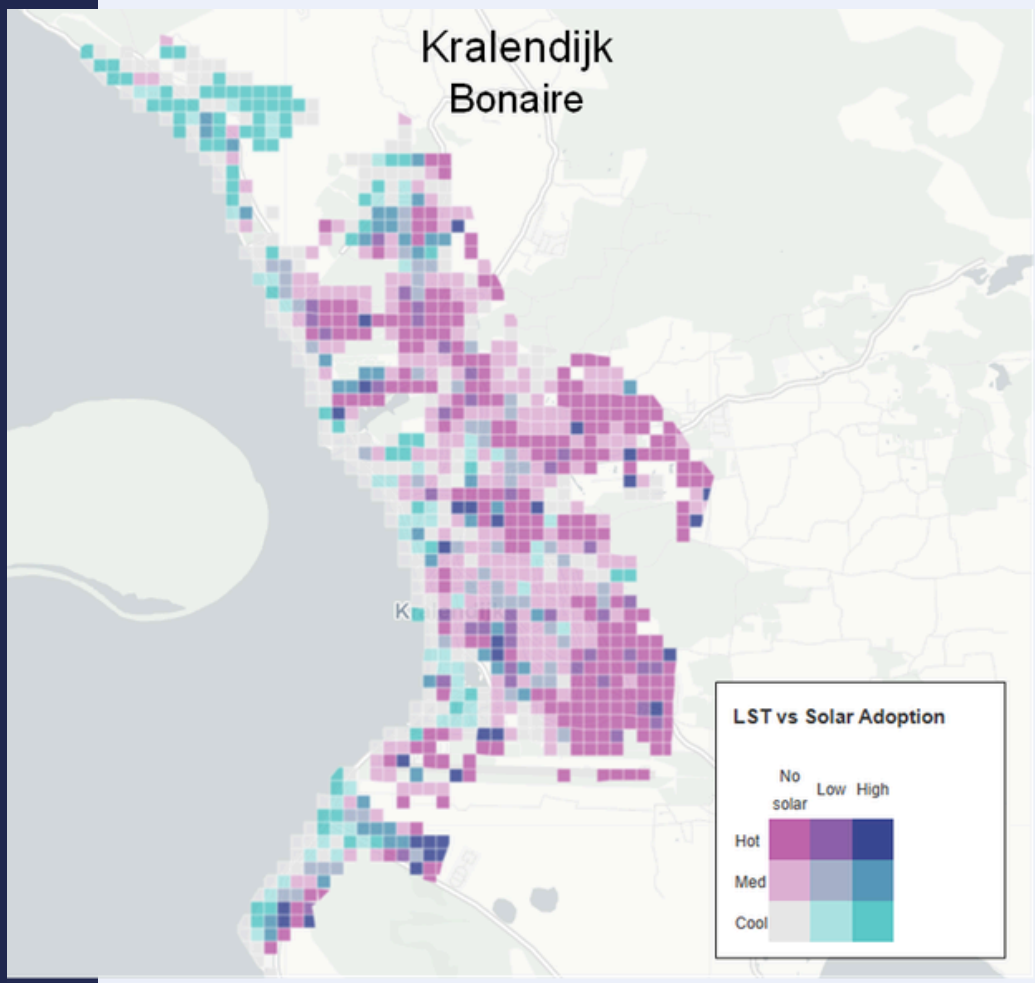
Update grid infrastructure to allow wider adoption of grid-connected rooftop solar

Use Earth Observation data to identify priority areas for heat-related interventions

Consider small-scale Community Energy Storage systems to diffuse high adoption costs of hybrid solar systems

Bonaire is making great strides towards its energy transition but the benefits are inequitably distributed among residents. Earth Observation data, combined with community-led initiatives, can ensure that this energy transition is just.

Relationship Between Rooftop Solar Adoption and Land Surface Temperature in Kralendijk, Bonaire



- High land surface temperatures and low rooftop solar adoption is concentrated in Bonaire's poorer neighborhoods - especially Tera Korá in the southeast
- Desirable neighborhoods such as Santa Barbara in the northwest have the highest rooftop solar adoption rates but also the lowest land surface temperatures

Heat & Inequity in Curaçao

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As climate change intensifies, Curaçao faces growing exposure to extreme heat. As a small, highly urbanised island, heat risk, infrastructure patterns, and socio-spatial segregation are tightly coupled - yet assessments linking environmental exposure to social vulnerability remain absent. To address this gap, this study maps heat burden across Curaçao's census tracts, revealing how LST varies with different socioeconomic and demographic characteristics. This supports fairer and more targeted adaptation strategies in a small-island context.

Findings & Recommendations

Spatial autocorrelation confirms that heat is clustered and not randomly distributed

More densely populated areas experience disproportionately higher heat burden, consistent with urban heat island dynamics

Renters have less ability to choose cooler residential locations, so tend to cluster in older and denser urban areas

Neighbourhoods with higher rates of chronic illness are exposed to significantly elevated LST

Prioritise cooling interventions in high density urban cores, e.g. tree canopies and permeable paving

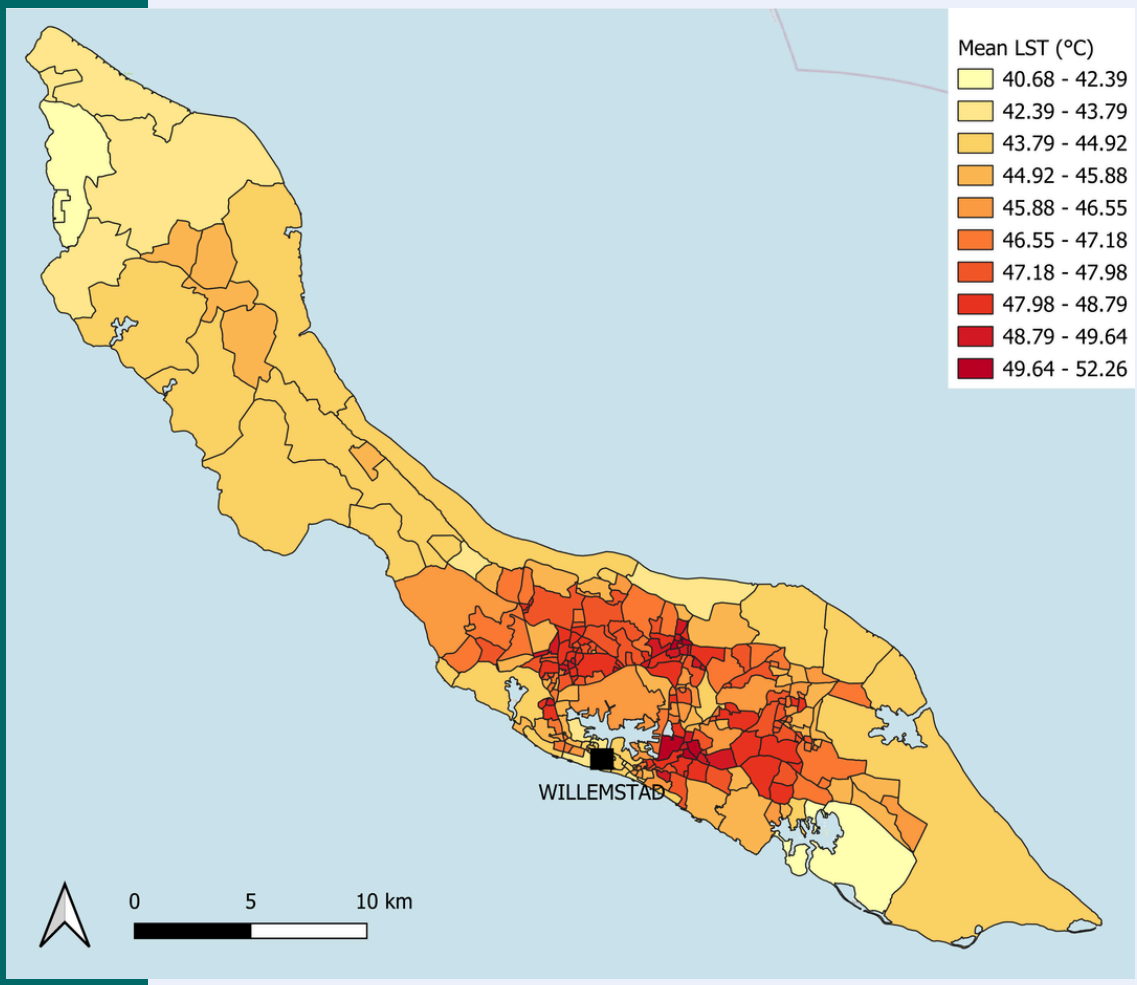
Target support measures in neighbourhoods with high rates of non-communicable diseases

Reform rental housing standards to include thermal resilience, e.g. airflow and ventilation standards

Embed spatial thinking into urban planning policy, since heat mitigation in one neighbourhood can benefit adjacent areas

Addressing heat inequity in Curaçao requires policies that recognise where vulnerability and exposure intersect - this requires accurate Earth Observation and Census data

Mean land surface temperature (LST) by neighbourhood, Curaçao, June-September 2023



- Most intense heat is concentrated in and around the built up capital, Willemstad, with LST values reaching 49–52°C
- Northwest and southeastern edges of the island record the lowest LST values, consistent with coastal breeze patterns and lower built-up density

Earth Observation for flood risk management

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Climate change is increasing the frequency of extreme rainfall events. The November 2022 floods on Bonaire closed the hospital and schools and damaged the surrounding reefs. In January 2026, a court ruled that the Netherlands had failed in its duty to protect the island. Earth Observation (EO) satellite data can help to monitor and forecast flooding, and such data is already openly available for the Dutch Caribbean. However, raw data alone is insufficient. It must be translated into products that local users can act on. Based on 21 stakeholder interviews, this study examines how EO data can be translated into entrepreneurial flood risk management services on Bonaire.

Findings & Recommendations

The data is not the problem. It is available. What is missing is the service to turn it into usable products.

Four needs recur. Restoring dams and saliñas, better drainage, faster early warning, more EO awareness.

Funding is the barrier. Project-based money means services rarely outlive their pilot.

Awareness is low and uneven. Most users struggle to conceptualise EO, though nature organisations are an exception.

Fill the service-provider role. Turn raw data into tools non-technical users can understand.

Adopt a regional approach. A single image spans many islands, so a multi-island service is more cost-effective.

Anchor EO flood risk services in public funding, as commercial-only models are unviable in a small island market.

Work through a local champion. Trust drives adoption, and local ownership is essential.

The potential of EO data for flood risk management on Bonaire is clear, but realising it requires more than the data itself: a service to make it usable, funding to keep that service alive, and a local context that turns it into action.

Ramsar Site Boundaries

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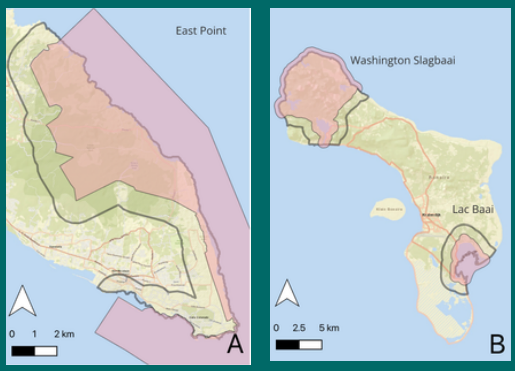
Ramsar site are internationally protected wetlands; climate change threatens the nature they preserve. This thesis measures the rigidity of boundaries of Ramsar sites on Aruba and Bonaire to identify the influence of buffer zones. 'Boundary rigidity' defines the gradient at the borders of protected areas, identifying areas of 'hardness' and 'softness' where PAs abut human-dominated areas abruptly or occupy a shared transition space, respectively. Further, interviews investigate the broader use cases of remote sensing technologies in the Dutch Caribbean.



Findings & Recommendations

'Paper borders,' such as Ramsar site and buffer zone borders, do not appear to align with an identified 'hard' boundary, indicating a soft transition between zones.

Woody coverage and lacunarity analyses show buffer zone vegetation that is consistent with Caribbean habitats, serving as baseline habitat indicators.

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.

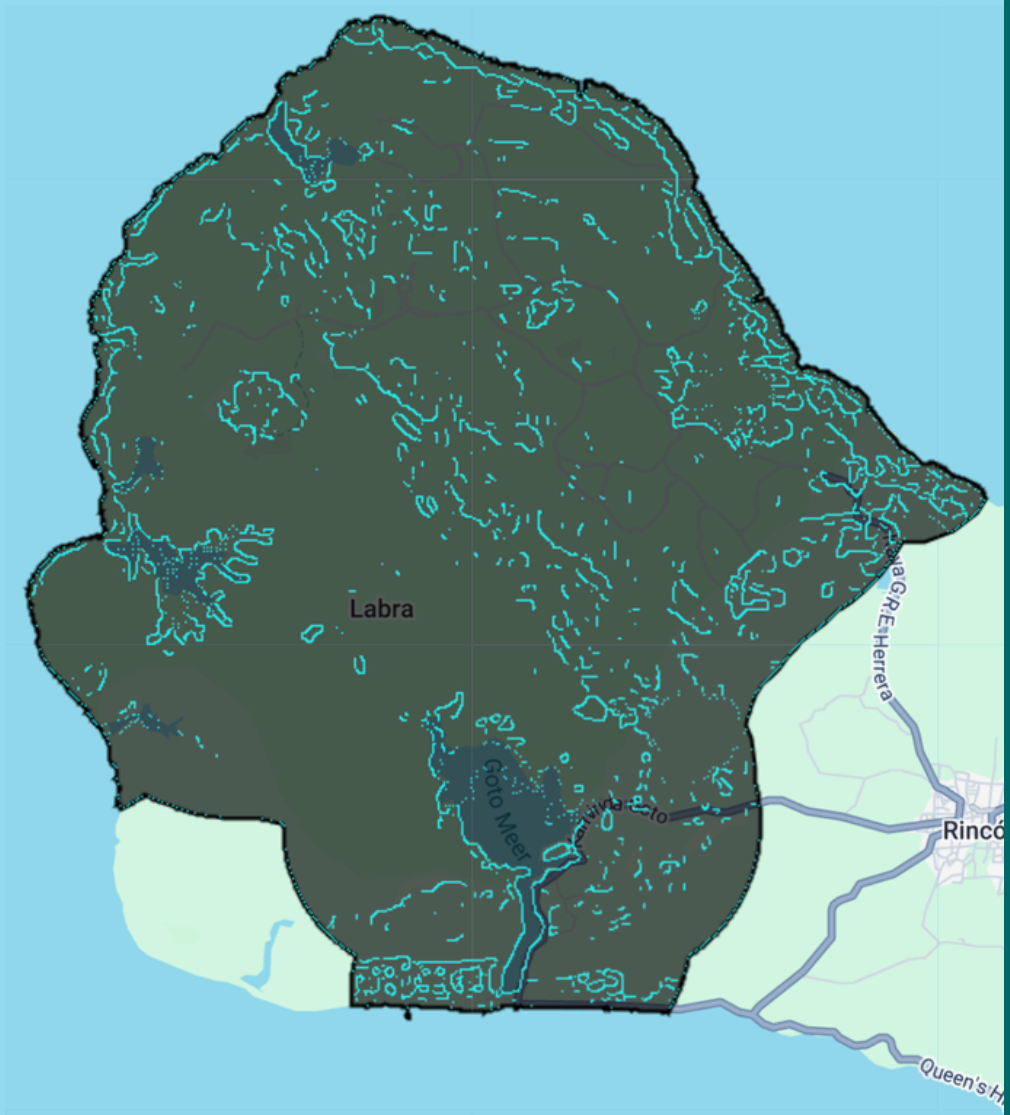
A Dutch Caribbean 'Digital Earth' is a welcome idea, though faces similar challenges to current EO use.

Physical infrastucture is missing and without it, digital EO skills will remain underused.

EO programs must be co-created and co-managed with Dutch Caribbean nature organizations to ensure relevancy.

Open-source data and replicable EO methods can boost nature monitoring in the Dutch Caribbean.

Ultimately, remote sensing is an incredibly powerful and accessible tool with great potential for future adoption in nature monitoring in the Dutch Caribbean.



- A canny edge detection algorithm can identify boundaries by identifying lines separating zones of spectral variance, such as in this visualization of Washington Slagbaai Ramsar site.

- Boundaries do not follow the 'paper borders' assigned to a protected area, an indication a gradual transition in the human-nature interface.

Legal Governance

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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.

Findings & Recommendations

The fragmentation in data openness and licensing resulting from the diversity of EO data sources affects data accessibility.

The fragmented regulatory framework governing the use of EO data, which encompasses spatial planning principles, environmental legislation, Dutch law, EU policy and local governance arrangements, affects the usability of such data.

The constraints imposed by fragmented national security regulation on the export of EO data create uncertainty regarding the long-term sustainabiility of such data.

Introduce a public interest data-sharing agreement and implement standardised management of key environmental monitoring data for repeatable access.

Establish trusted data-sharing partnerships through bilateral or regional cooperation and develop exceptions for environmental and climate purposes

Establish a cross-departmental advisory committee or governance framework to coordinate the use of EO data in the Dutch Caribbean

The use of EO data in the Dutch Caribbean reveals how fragmented governance, data access, and natioanl security regimes constrain the sustainability potential of EO and requires a coordinated governance framework for availability and usability of data.

Marine Cloud Brightening

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The objective of this thesis is to investigate the atmospheric and oceanic conditions around Bonaire and asses whether sea-salt aerosol spraying could effectively lead to Marine Cloud Brightening (MCB) or Marine Sky Brightening (MSB). These solar radiation modification strategies could potentially be deployed during marine heatwave events to create a local cooling effect and reduce the risk of coral bleaching around Bonaire. ERA5 reanalysis data is used to select representative heatwave events as case studies for Large Eddy Simulations (LES). Different aerosol spraying strategies will be tested in the LES to find the most optimal spraying strategy.

Photo: Adam Ferguson for The New York Times

Findings & Recommendations

MCB is a technology that increases aerosol concentrations in clouds, enhancing the reflectivity of the cloud and reducing the amount of solar energy reaching the sea surface

MSB is a technology that created a layer of fine sea-salt aerosol particles above the sea surface, reducing the amount of solar energy reaching the sea surface

MCB works best in atmospheric conditions with low marine clouds. Sufficient turbulent mixing is required to take the sea-salt particals to the cloud base

MSB works best in stable atmospheric conditions, in which the mist stays floating above the sea surface. No clouds are needed for this.

The ERA5 reanalysis climate data has a 0.25° × 0.25° grid (about 31 km resolution), which limits the precision of analysis around Bonaire

Early results indicate that the low marine clouds above Bonaire are not suitable for MCB, while specific heatwave events show potential for MSB implementation

Earth Observation (reanalysis) data can be used to assess atmospheric conditions for MCB and MSB implementation during marine heatwaves around Bonaire. This thesis study is ongoing and planned to be completed in December.

Sargassum, Tourism, and Bonaire

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The *Sargassum* bloom that first occurred in 2011 is hurting the economy of the Caribbean by deterring tourists. By modelling official tourism statistics against EO-detected *Sargassum* records, which are verified with ground-truth observations, I discovered that no immediate risk is present in Bonaire, which presents opportunities for the sector. I also confirm that supplying EO data with ground-truth observation can increase the accuracy of detection.

Findings & Recommendations

Ground truth observations and EO-based detections should be used to supplement each other for a more reliable, continuous measure of coastal *Sargassum* exposure.

No robust causal relationship between *Sargassum* influx and tourism dynamics is found for Bonaire.

Sargassum's socio-economic impact is beyond its influence on tourism.

The lack of impact of *Sargassum* on Bonaire can be an opportunity for local tourism businesses.

EO-derived products and corresponding datasets should be available with sufficient temporal coverage.

Integration of EO data and ground-truth observation, especially from citizen-science projects, is beneficial.

EO's advantage is the inter-island comparablility provided by same level of EO data.

Establishing transferable data pipelines for EO data will reduce the analytical cost of decision-making.

Earth observation from publicly funded projects, joined to civil statistics, can answer governance questions for the Dutch Caribbean.

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

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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

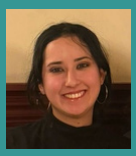
Through spectral indices of high resolution observations, spatial indicators could be developed to measure coastal change, natural buffers, built-up intensity, and external exposure

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.



Please note that 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 in the thesis-repository of TU Delft when completed.

Our wishes for EO in the Dutch Caribbean...

Maxime Léger

Greater resource and data sharing between Dutch Caribbean islands and other island nations would boost collective data capabilities and regional nature monitoring.

Deploy a Digital Earth!

Demi Timmers

Earth Observation won't change tourism decisions on its own. What's missing is the governance bridge between the satellite and the operator.

Zoey Liu

It would be nice that more EO products is available to the public, and more synergies between EO and other data.

Kim Bosch

More awareness for the capabilities of Earth Observation.

Alyssa Wells

Earth observation data that enhances decision-making and collaboration between communities, businesses, and municipalities.

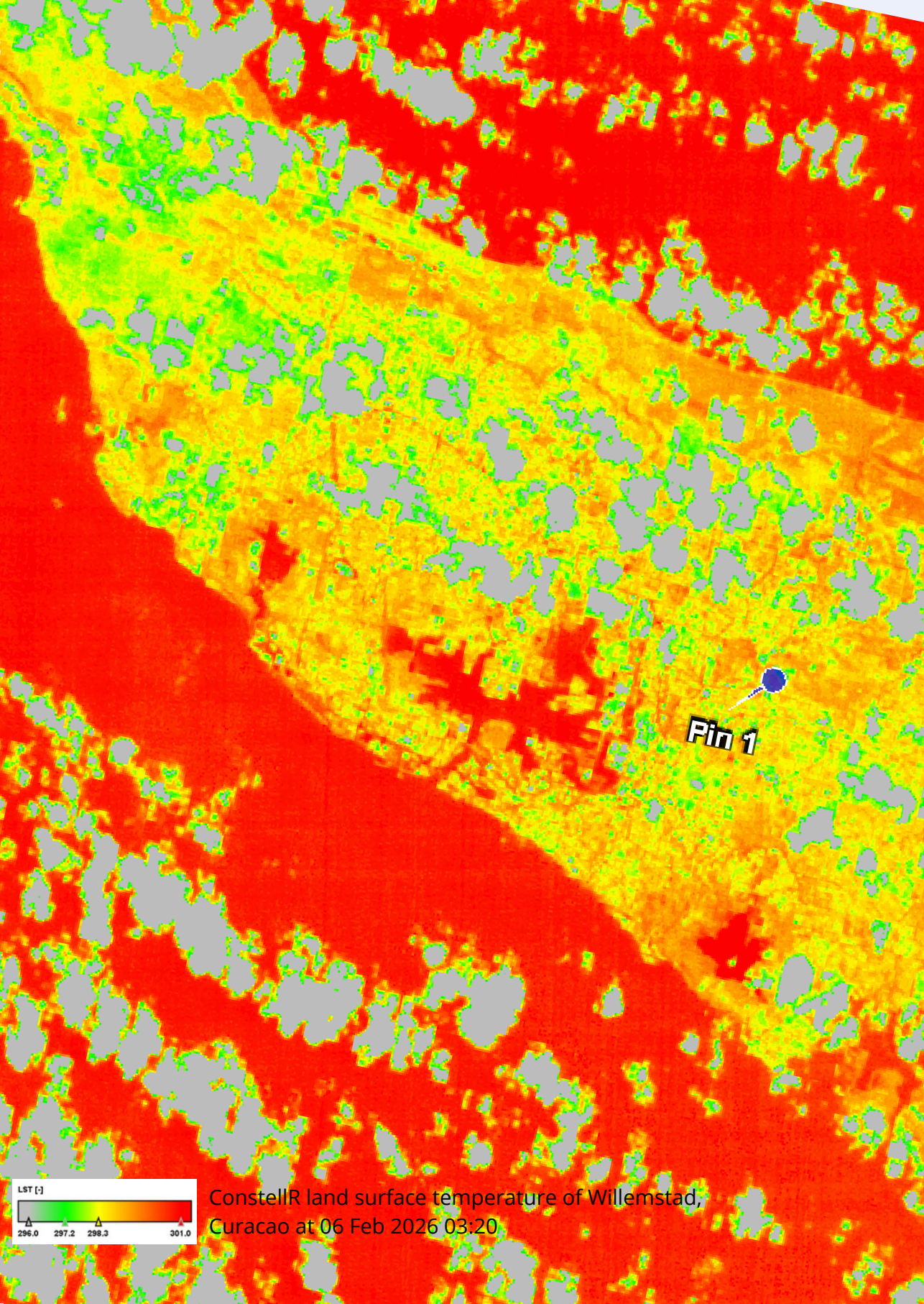
Christopher Hastings

Better collaboration between Earth observation agencies and local entities can help find solutions to complex issues.

Acknowledgements

We kindly would like to thank the Netherlands Space Agency (NLSA) as case holder, the Leiden Delft Erasmus (LDE) center for coordinating the thesis labs, Joris Timmermans as academic coordinator, Saskia Postema as network coordinator, Peter Batenburg for initiating the project.

Furthermore, we would also like to thank the European Space Agency for supporting this Thesis Lab by providing access to high resolution satellite observations through their Earth Observation User Services Portal. Specifically the use of high resolution VNIR data from Neo Pleiades from Airbus Intelligence (project PP0109175), and high resolution thermal observations from ConstellR (project PP0109175), were vital in exploring the potential of earth observation for the Dutch Caribbean.



ConstellR land surface temperature of Willemstad, Curacao at 06 Feb 2026 03:20

ABOUT THE LDE THESIS LABS PROGRAM

Coordinated by Esther van der Ent
Programme Manager LDE Thesis Labs

The research you have just read was carried out within the LDE Thesis Labs program; a transdisciplinary master's programme run jointly by Leiden University, Delft University of Technology, and Erasmus University Rotterdam. Each lab brings together a group of students from different disciplines, united by a single real-world challenge set by an external organisation. Students work on their own individual thesis while simultaneously contributing to a shared interdisciplinary result that none of them could have produced alone. The booklet you are holding now!

What makes the thesis labs distinctive is not just the mixing of disciplines, but the willingness to engage with complexity. Students learn to look beyond the boundaries of their own field, to question their assumptions, and to find unexpected connections across perspectives.

To support the interdisciplinary process, students follow a programme of 12 bi-weekly sessions led by an academic coordinator. The next pages give a closer look at how that journey unfolded!

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THE JOURNEY

While each student works independently, workshops, enrichment sessions and excursions, are organised to get a grip on the complexity of the main challenge. Student meet up with professionals, academic experts and societal partners. Together they learn, share and collaborate and contribute to a common, interdisciplinary result with real impact.

#0 Online Meeting, In January we organized a short get together with our lab team and the academic coordinator. Here, students met each other for the first time and were given the opportunity to ask already questions about the thesis assignment and lab program

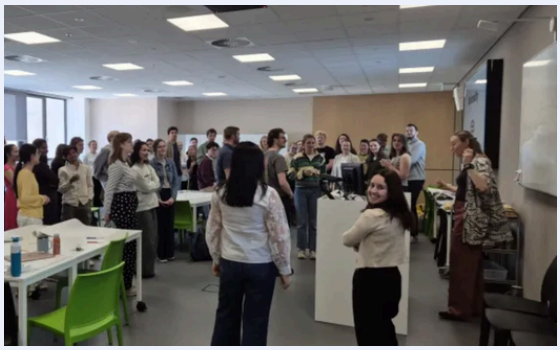
#1 Kick-off, In February, the LDE Thesis Lab program kicked off! Students met up with their academic coordinator, general coordinator and had a dedicated sessions with Netherlands Space Agency case holder to ask specific questions

#2,3,4 8,9 Enrichment. Enrichment sessions were organized, where we focused on getting a grip on the complex system Climate Change, Remote Sensing, Legislation, Cultural Heritage,

#5 Pressure Cooker Day: During a LEGO SERIOUS PLAY, students created an envisioned future related to the lab challenge, and identify new directions of innovations.

#6 Round Table. Halfway through the program, we had an elaborate discussion with the case holders and invited experts.

#7 Bootcamp Day. We organized a Science Communication workshop, and learned about storytelling; how do we tell our research in an interesting way?



 # 10 Prepare for the Final Event
All labs came together to prepare for their end events. Students got together to create this booklet and prepare for a spectacular final event!

#11 Final Event During the Copernicus Coastal Monitoring workshop (organised on the 2nd of July in Rotterdam, the Netherlands), the students share the knowledge they have gained with the case holder.