Remote-sensing and classification of benthic landscapes for satellite derived bathymetry

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Master thesis

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Physics of Aquatic Systems Laboratory, EPFL - Switzerland

Summary

- **Introduction**
  - Satellite derived bathymetry, motivation and background
  - Physic principles in water surrounding
  - Aims of the thesis
  - Study site: South part of the new caledonian lagoon
- **Materials**
- **Methods and results**
  - Workflow
  - Image pre-processing
  - Bottom type and water classification
  - The number of clusters
  - Empirical modeling
- **Discussion**
- **Conclusion**

Satellite derived bathymetry, motivation and background

Bathymetry, a key variable

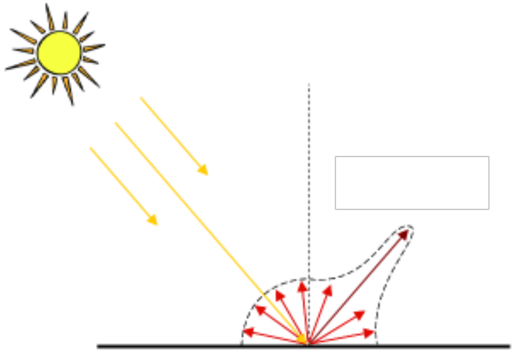
PRESENCE **:**

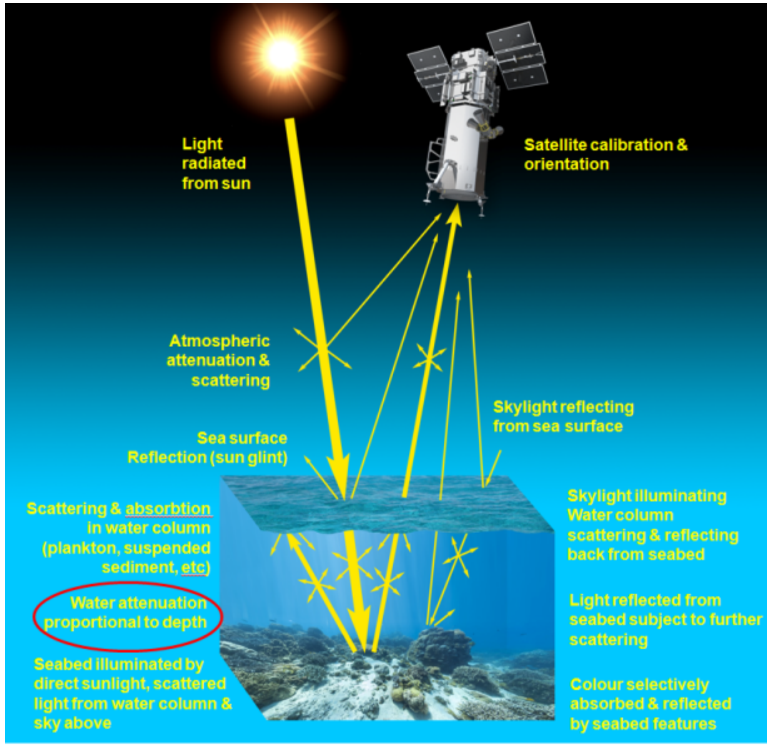
« PREssions sur les Ecosys- tèmes récifo-lagonaires de Nouvelle-CalédoniE »

- **Traditional bathymetric measurements:**
  - By echo-sounder at the surface
  - Expensive
  - Not achievable everywhere
- **Satellite derived bathymetry :**
  - Less accurate but…
  - Large scale water depth retrieval
  - High Resolution
  - Maximum depth : 25 – 30 meters
- **Sate of the art SDB:**
  - Empirical modelling
  - Semi-analytical modelling
  - Machine-learning
  - Classification

Physic principles in water surrounding

- **Radiance**
  - recorded by the satellite sensor
  - corresponds to a measure of the electromagnetic radiation flux emitted or reflected by a surface
  - dependent on :
    - The area of the source,
    - The view and solid angles of the sensor,
    - The wavelength
    - The irradiance





- **Reflection**
  - Diffuse or specular
- **Attenuation**
  - Come from the Absorption and the scattering

$$L(h) = L_s - L_b e^{-kh}$$

Physic principles in water surrounding

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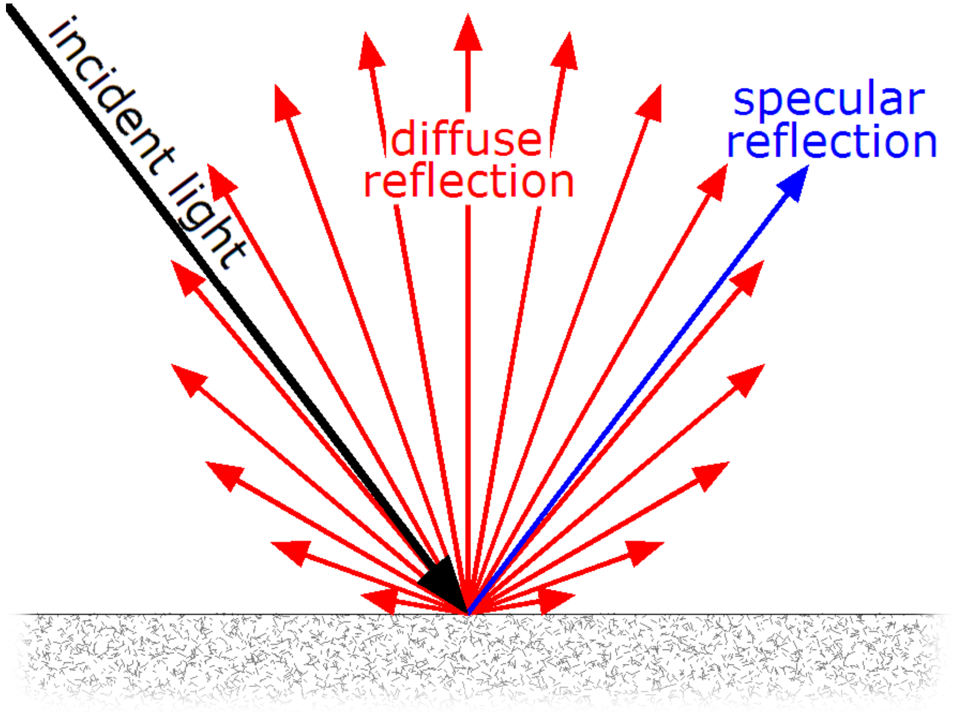


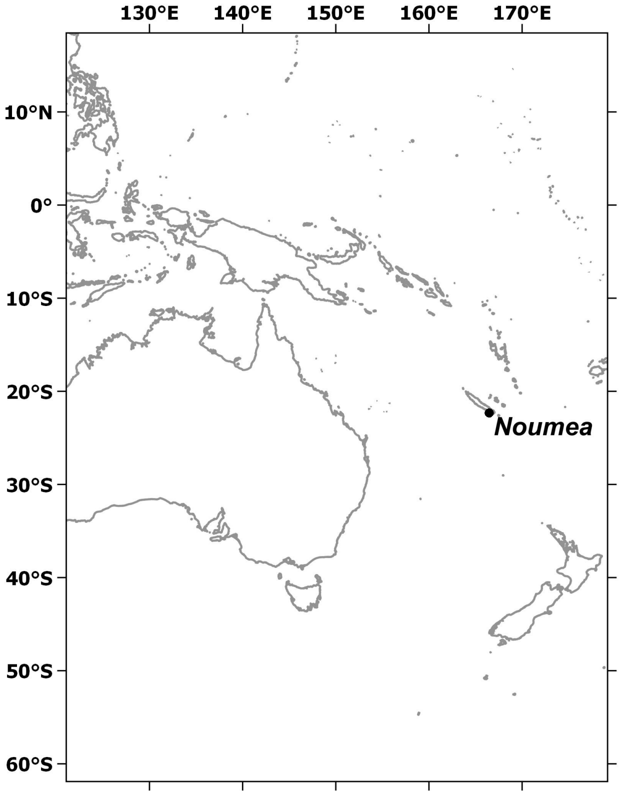
$$L(h) = L_G + L_s - L_b e^{-kh}$$

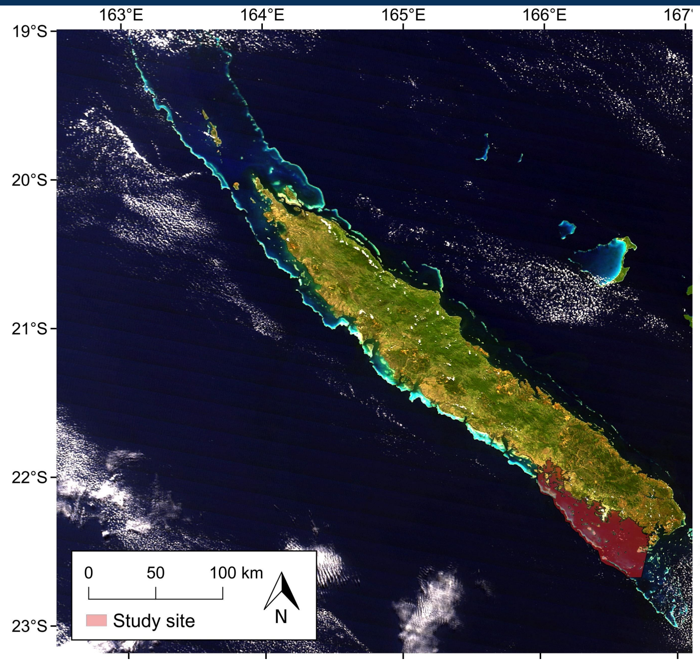
Aims of the thesis

- **Evaluation of empirical modelling**
- **Direct application on a specific multi-spectral sensor**
  - Discussion of technical issues and procedures
- **Scale of resolution**
- **Range of optimal depth prediction**
- **Proposed an approach by classification**

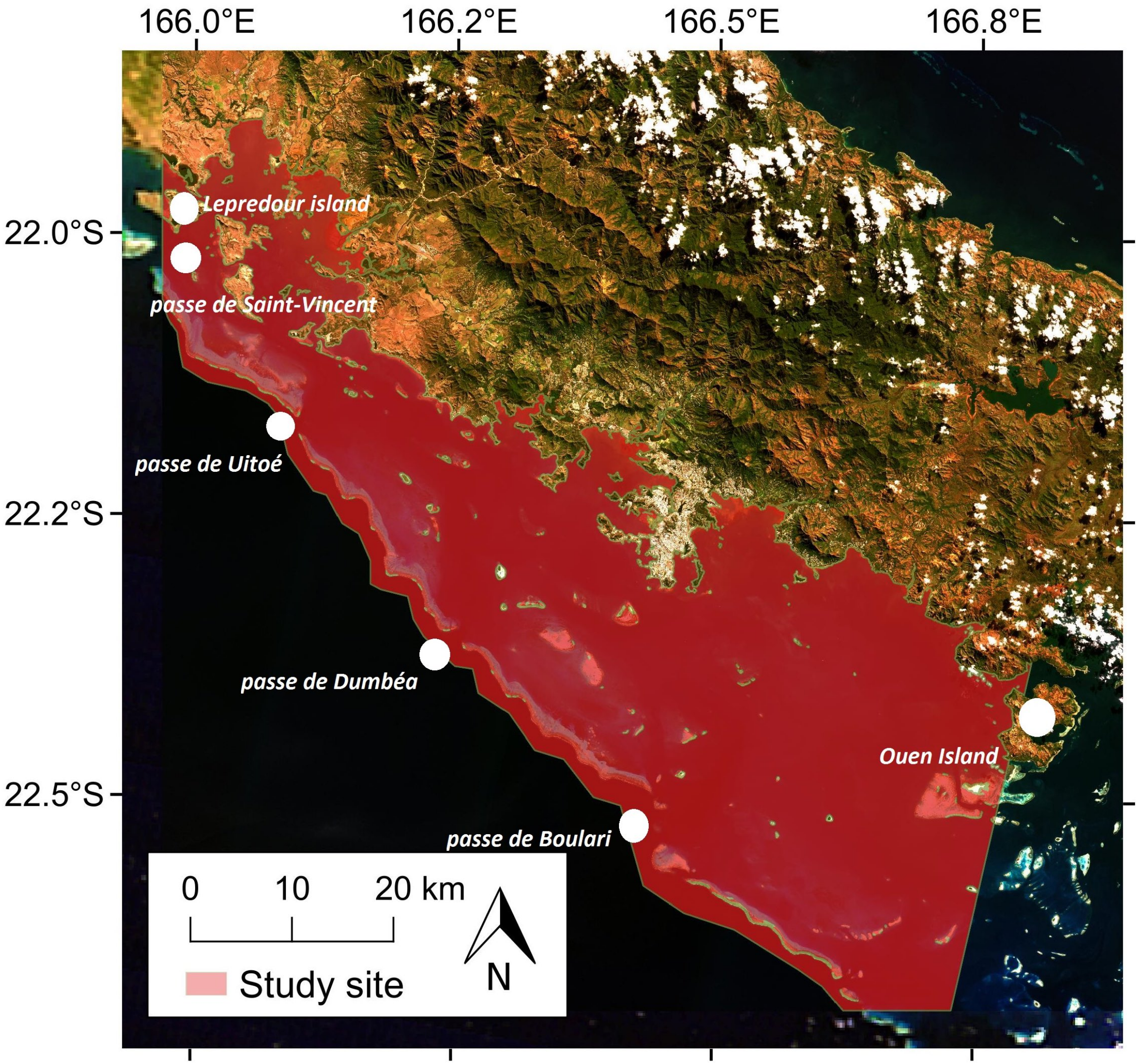
Study site: South part of the new caledonian lagoon

- **An extent of about 2’597.1332 km^2**
- **Semi-open area with four major channels through the barrier reef**





- **Offers a great number of in-situ measurements by echo-sounding**
- **set around the biggest city of the island : Nouméa**



Satellite sensor and Bathymetric dataset

Satellite sensor : Sentinel-2A

- Open data
- Multispectral ground resolution : 10 meters
- Additional blue band with shorter wavelength
- Sensor composed of several detectors, set on slightly different view angles

Bathymetric dataset

- Provided by the French national hydrographic service, SHOM,
- Represents 18’556’254 measurements
- Measured by by echo-sounder with an accuracy of +-2% of depth
- Only the measurements up to 30 meters are kept

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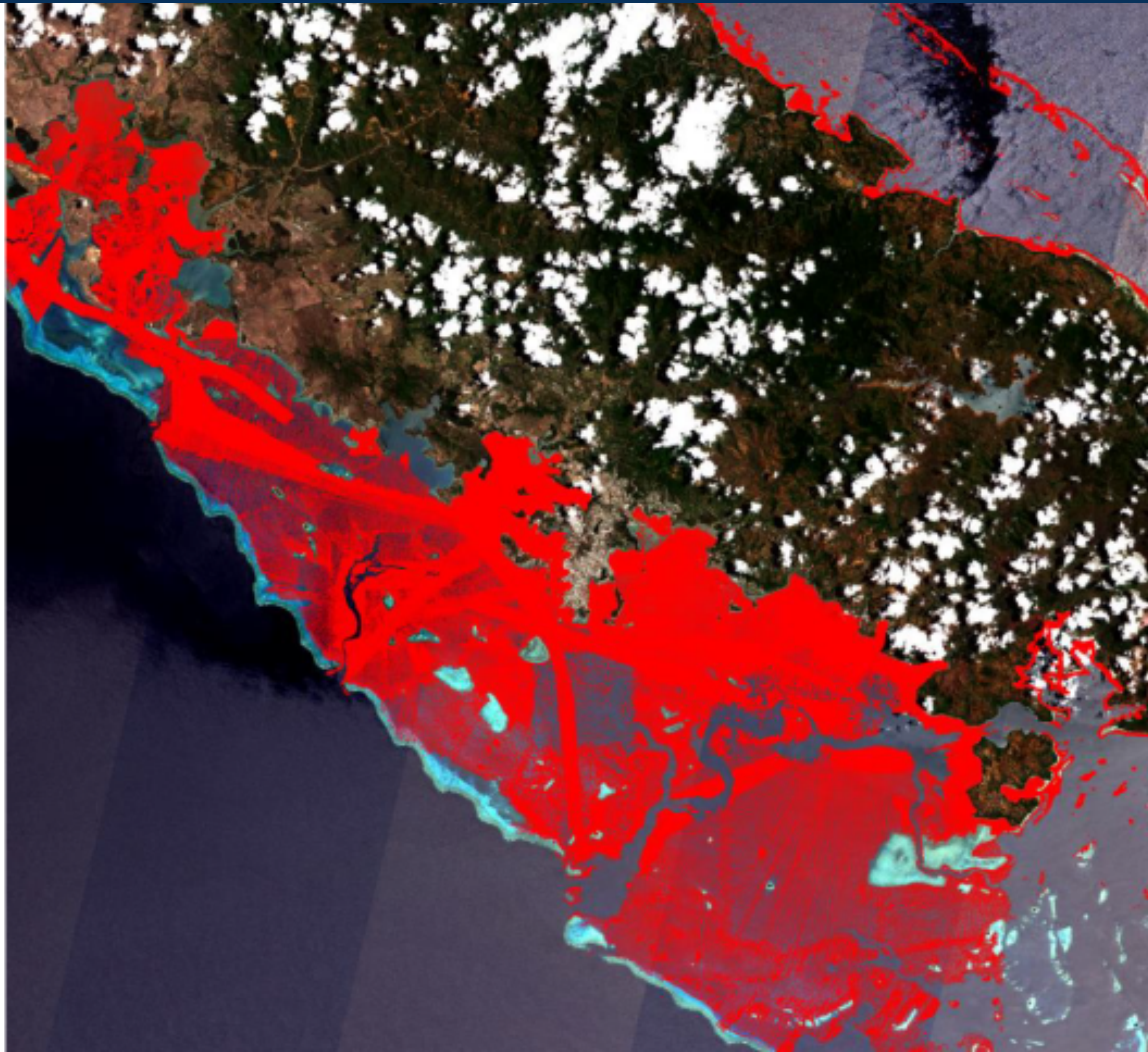
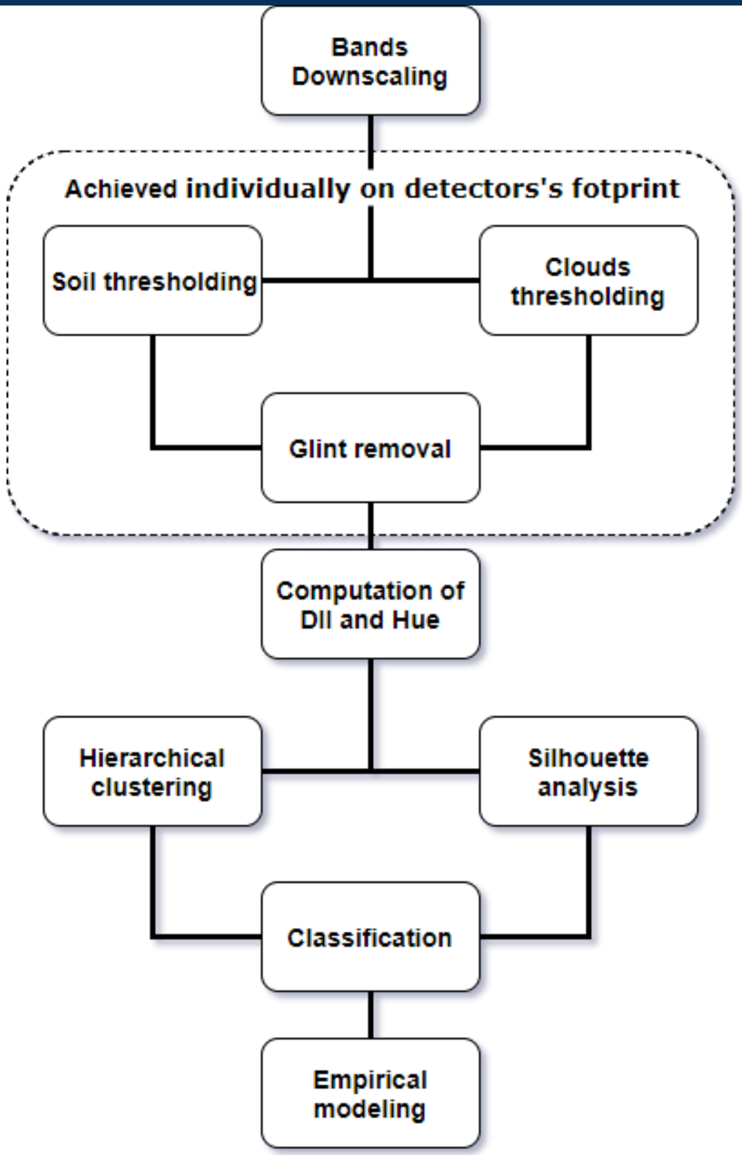


Method and results : Workflow

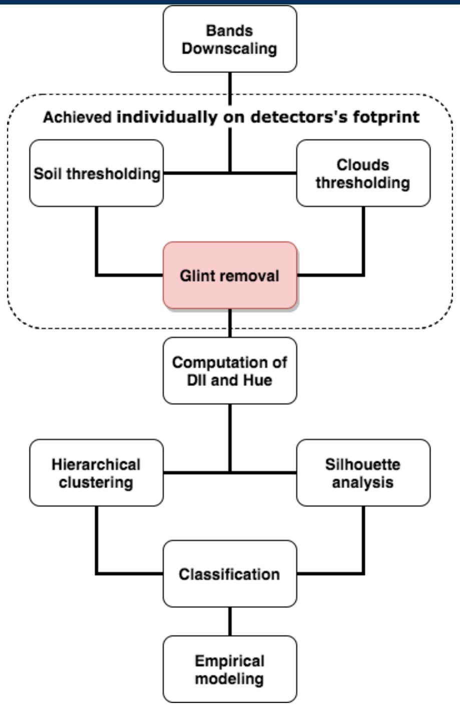


1. **Downscaling of 4 bands up to 10m**
2. **Image Pre-processing :**
   - Thresholding : empirically defined
   - Glint Removal
3. **Computation of DII and Hue as descriptors**
4. **Definition of the number of clusters :**
   - Analysis relying on Ward's method for Hierarchical clustering
   - Analysis relying on Silhouette index
5. **Bottom type and water classification by K-means :**
   - Aims at minimizing within-clusters inertia :

$$I(c, \mu) = \sum_{i=0}^{N} \left\| x^i - \mu_{c^i} \right\|^2$$

6. **Empirical models calibration**

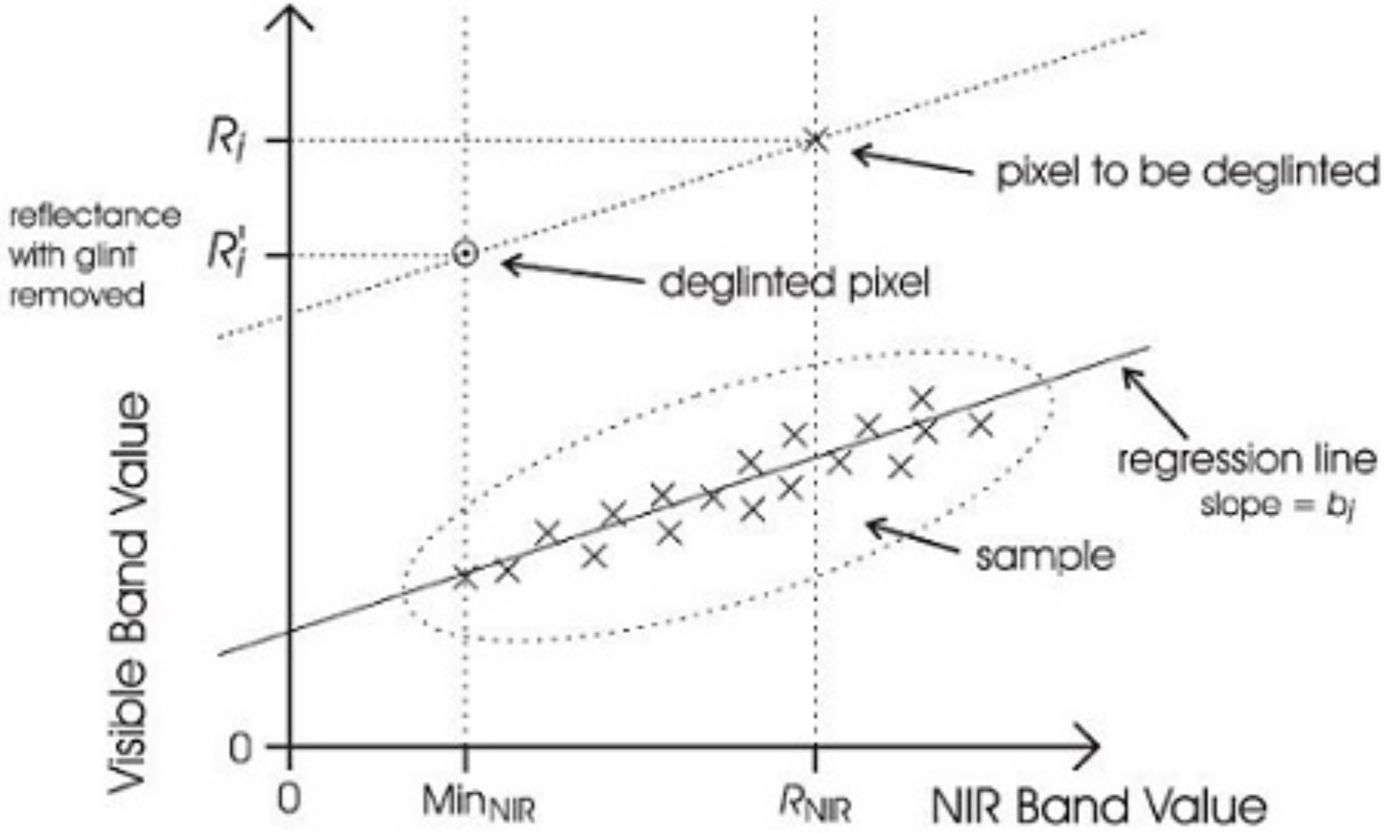
Method and results : Image pre-processing



Achieved on individually on detectors' footprint

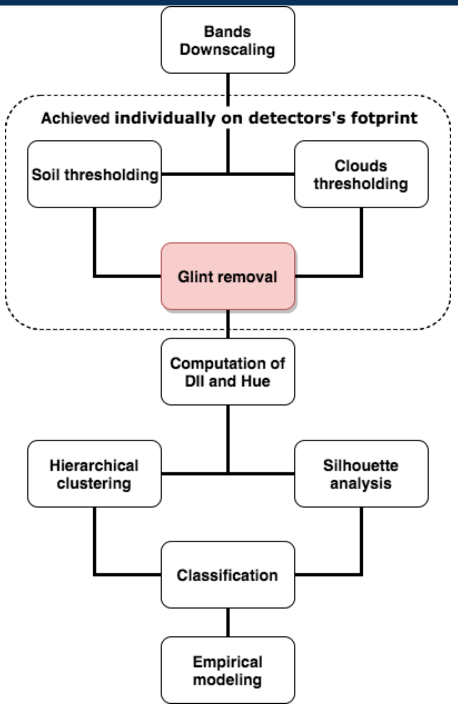
- **Sun Glint Removal :**

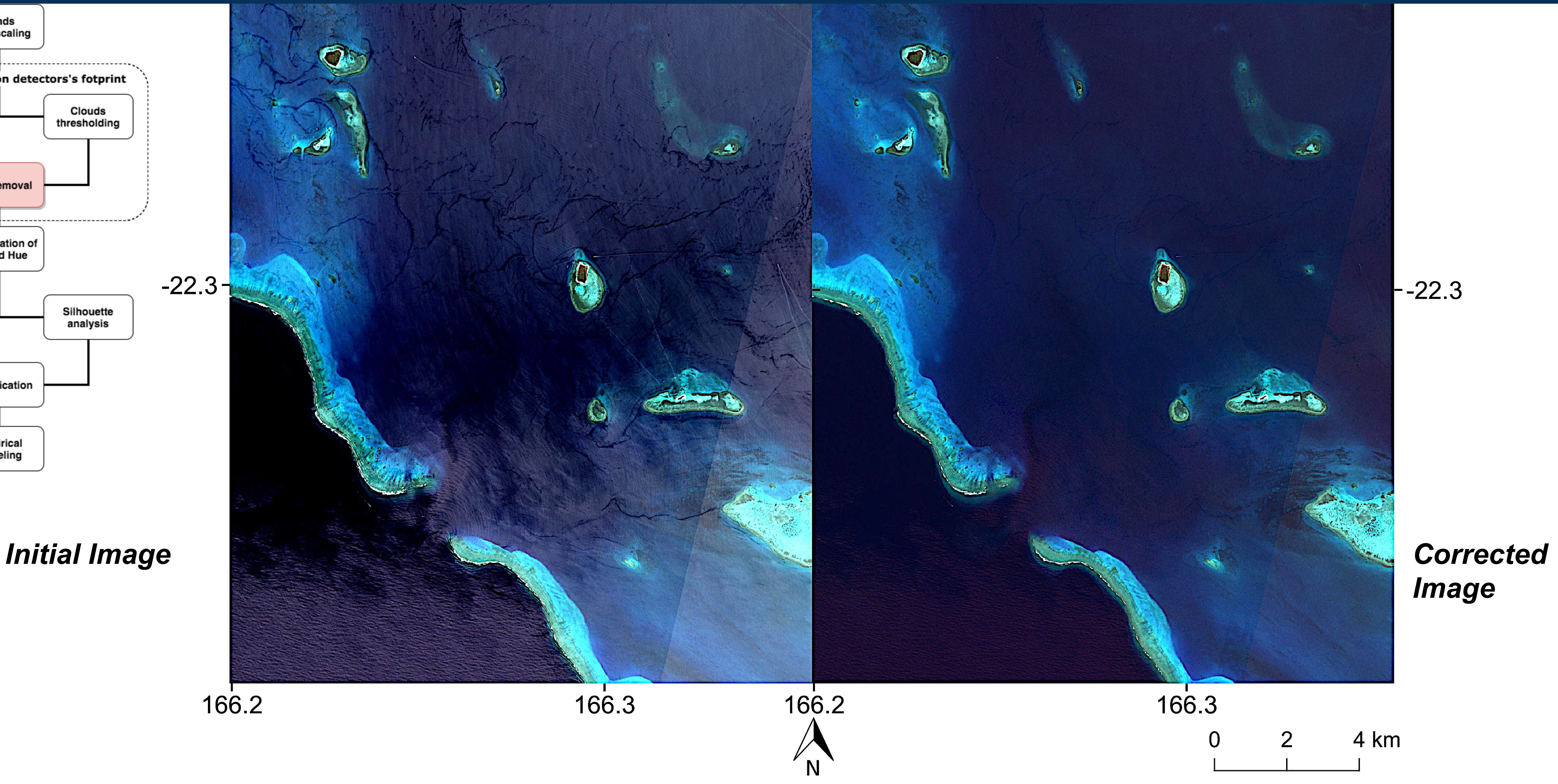
methods of Hedley et al., 2004



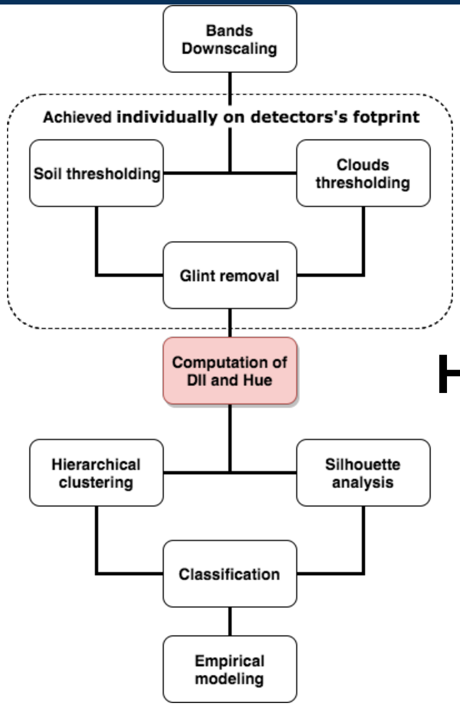
$$R'_i = R_i - b_i(R_{\mathrm{NIR}} - \mathrm{Min}_{\mathrm{NIR}})$$

Method and results : Image pre-processing





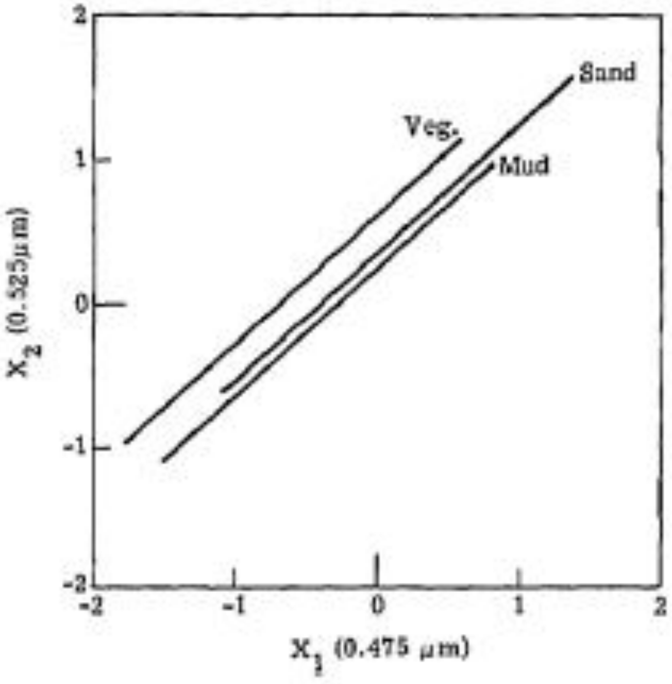
Method and results : Computation of the descriptors



Hue from HSV transformation

- HSV space is commonly used for aerial image classification
- We made the assumption the Hue is less dependent on radiation attenuation than Red, Green, Blue, Value or Saturation

Depth Invariant Index



$$X_i = \ln(L_i - L_i^{deep})$$

$$X_i = \frac{k_i}{k_j} X_j + d_{ij}$$

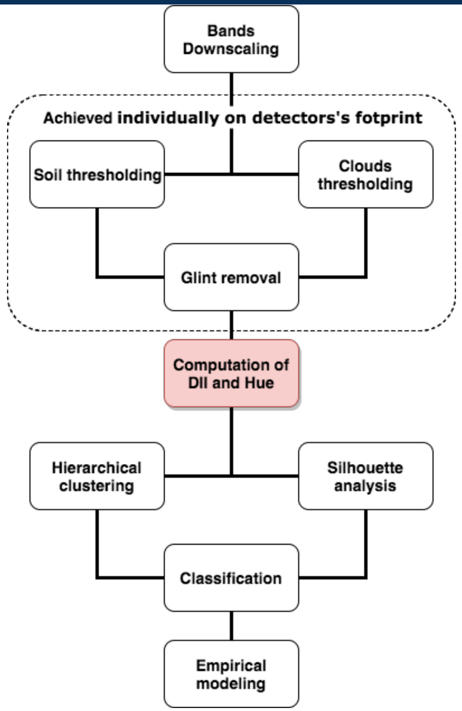
$$k_i / k_j = a + \sqrt{a^2 + 1}$$

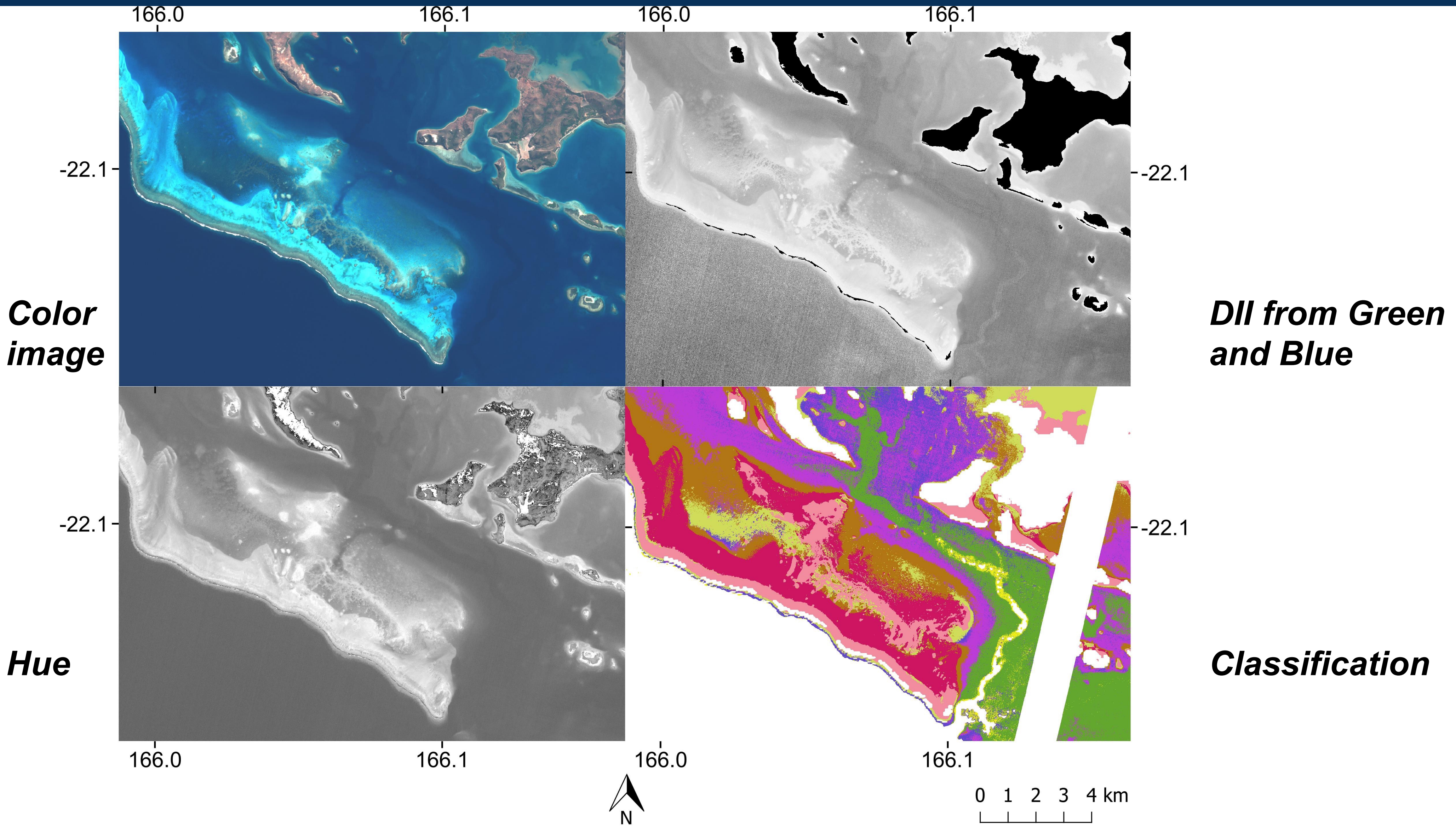
$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}}$$

$$\sigma_{ij} = \overline{X_i X_j} - (\overline{X_i}\,\overline{X_j})$$

$$d_{ij} = X_i - \frac{k_i}{k_j} X_j$$

Method and results : Computation of the descriptors





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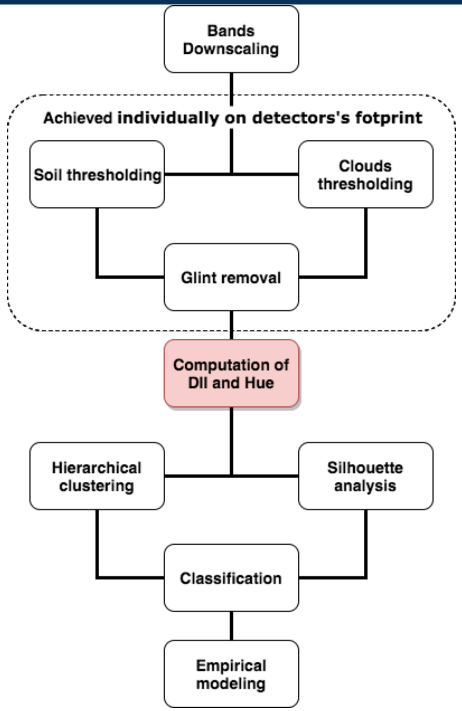

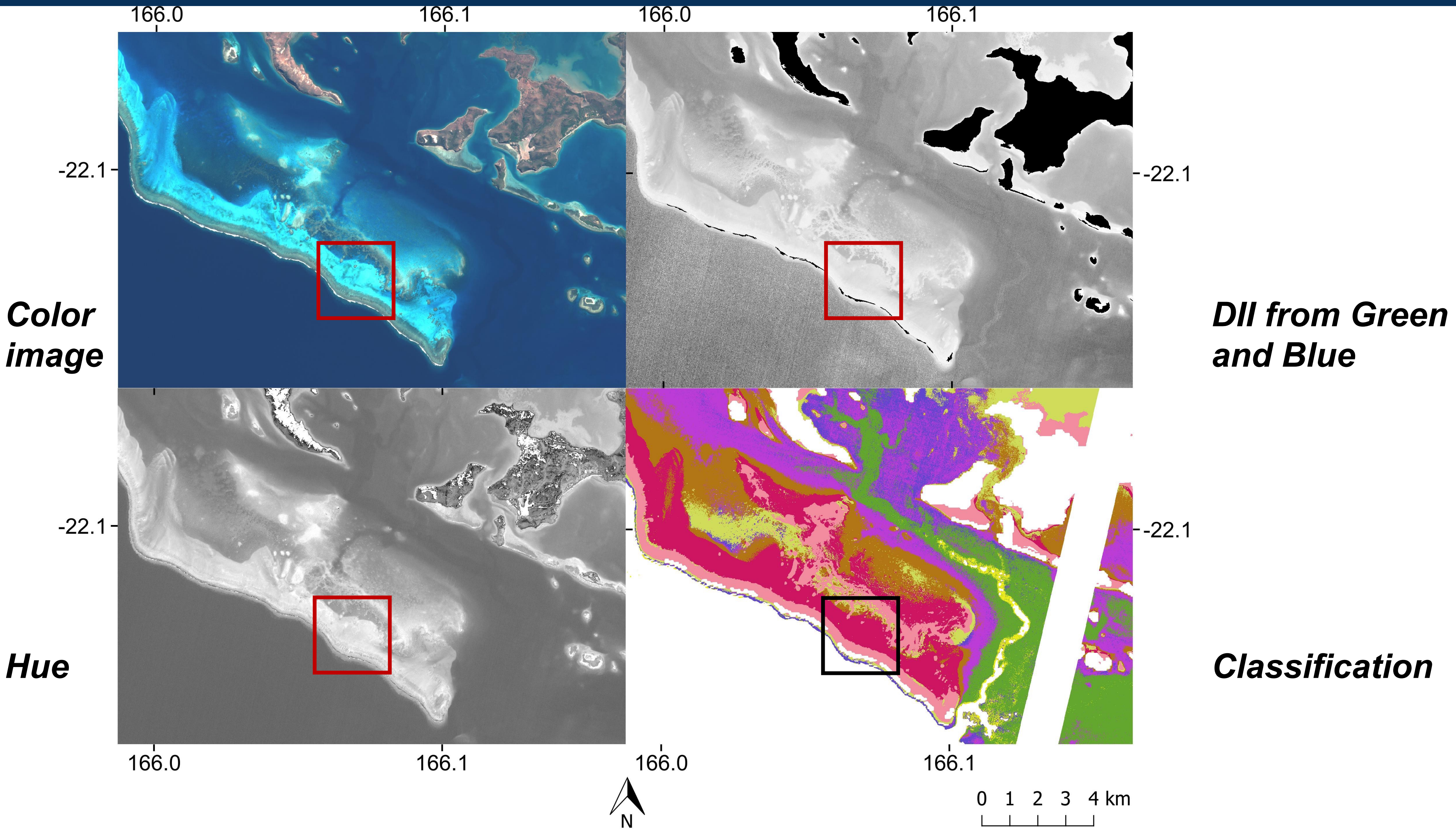

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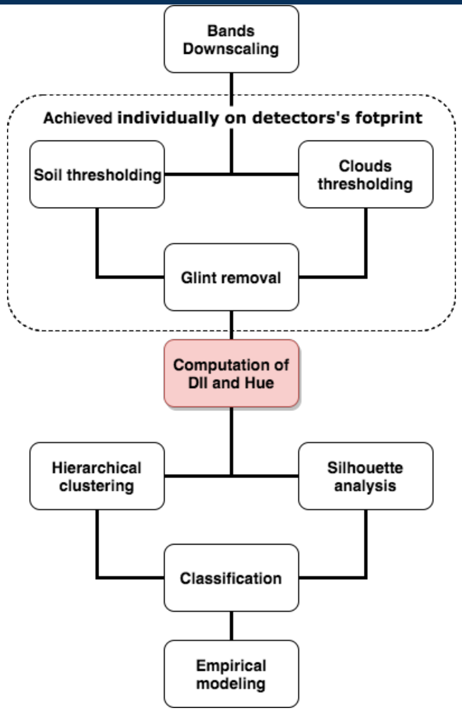
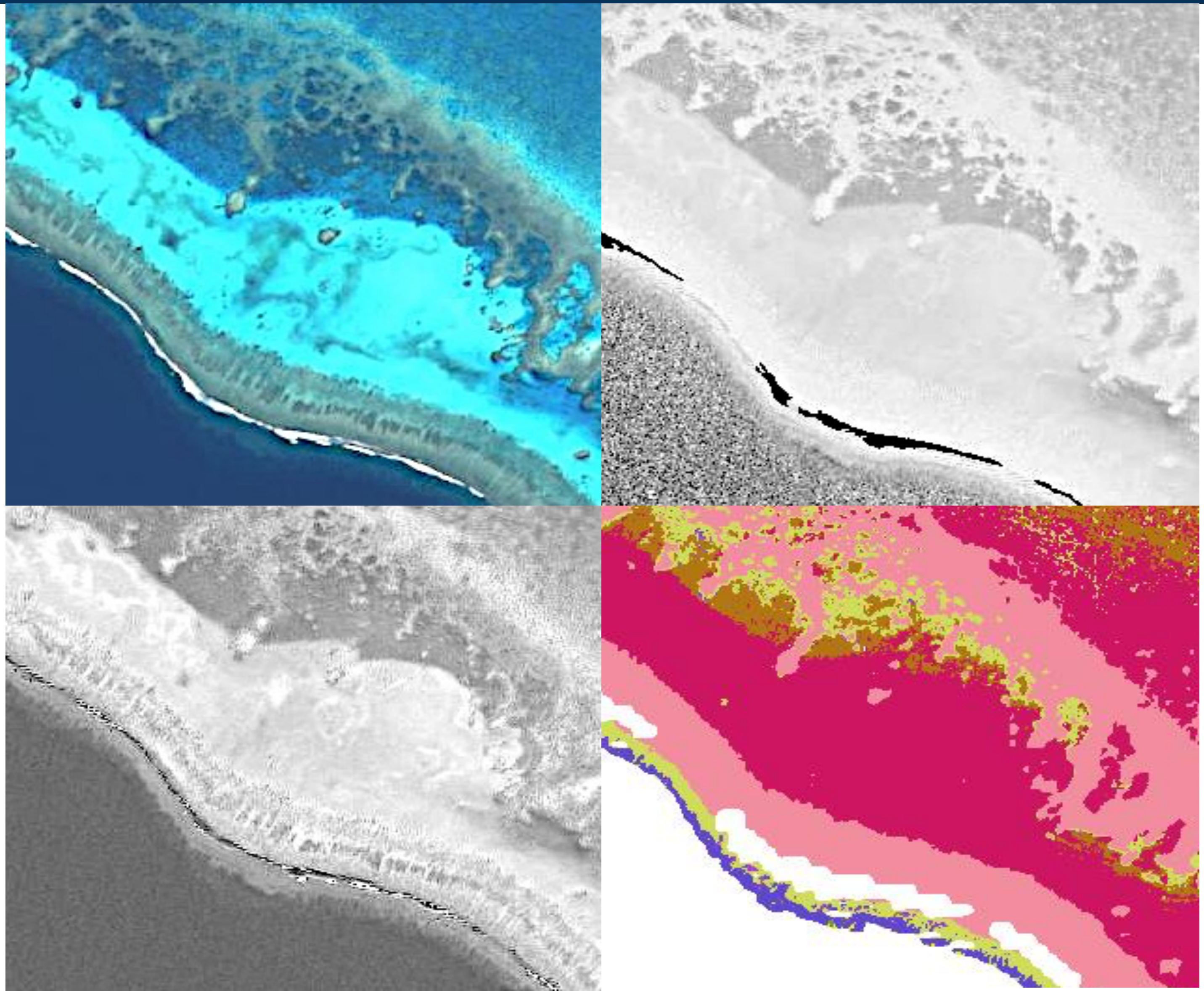




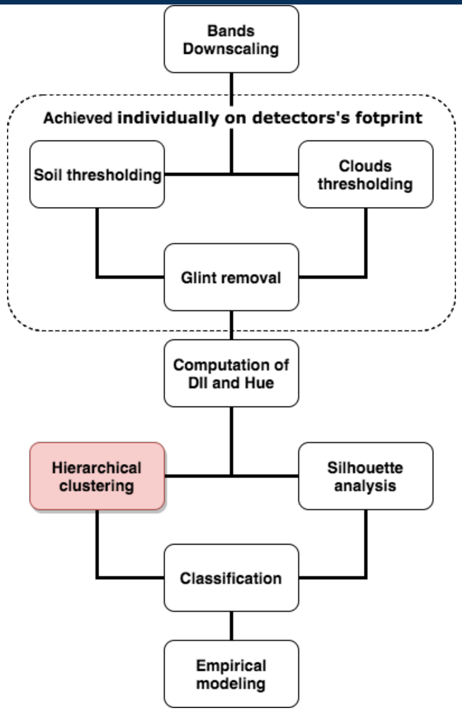
Color image

DII from Green and Blue

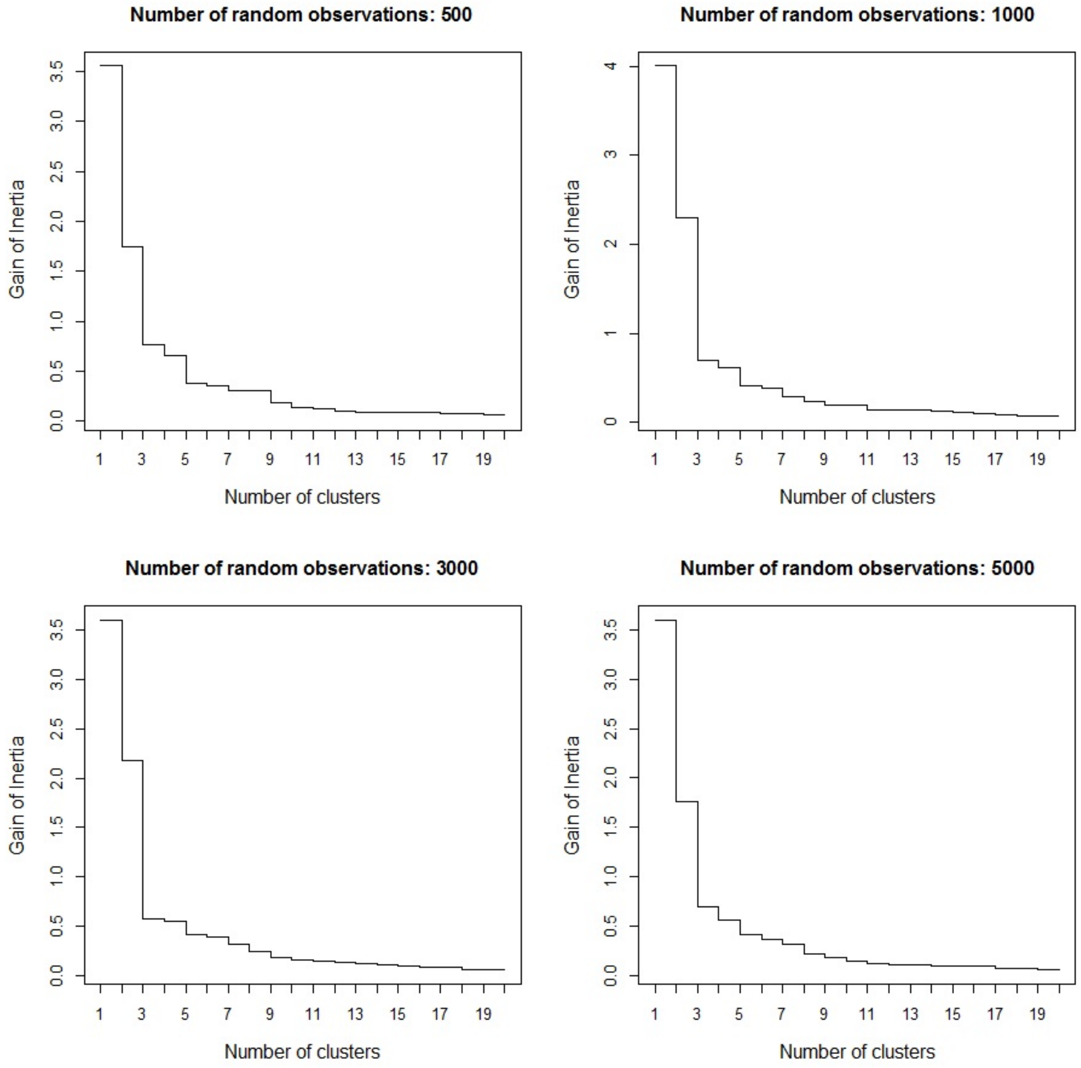
Hue

Classification

Method and results : The number of clusters



Without-cluster Inertia Loss



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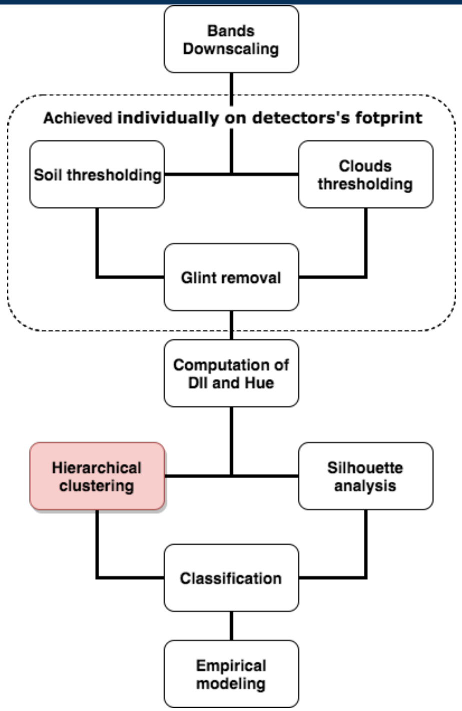

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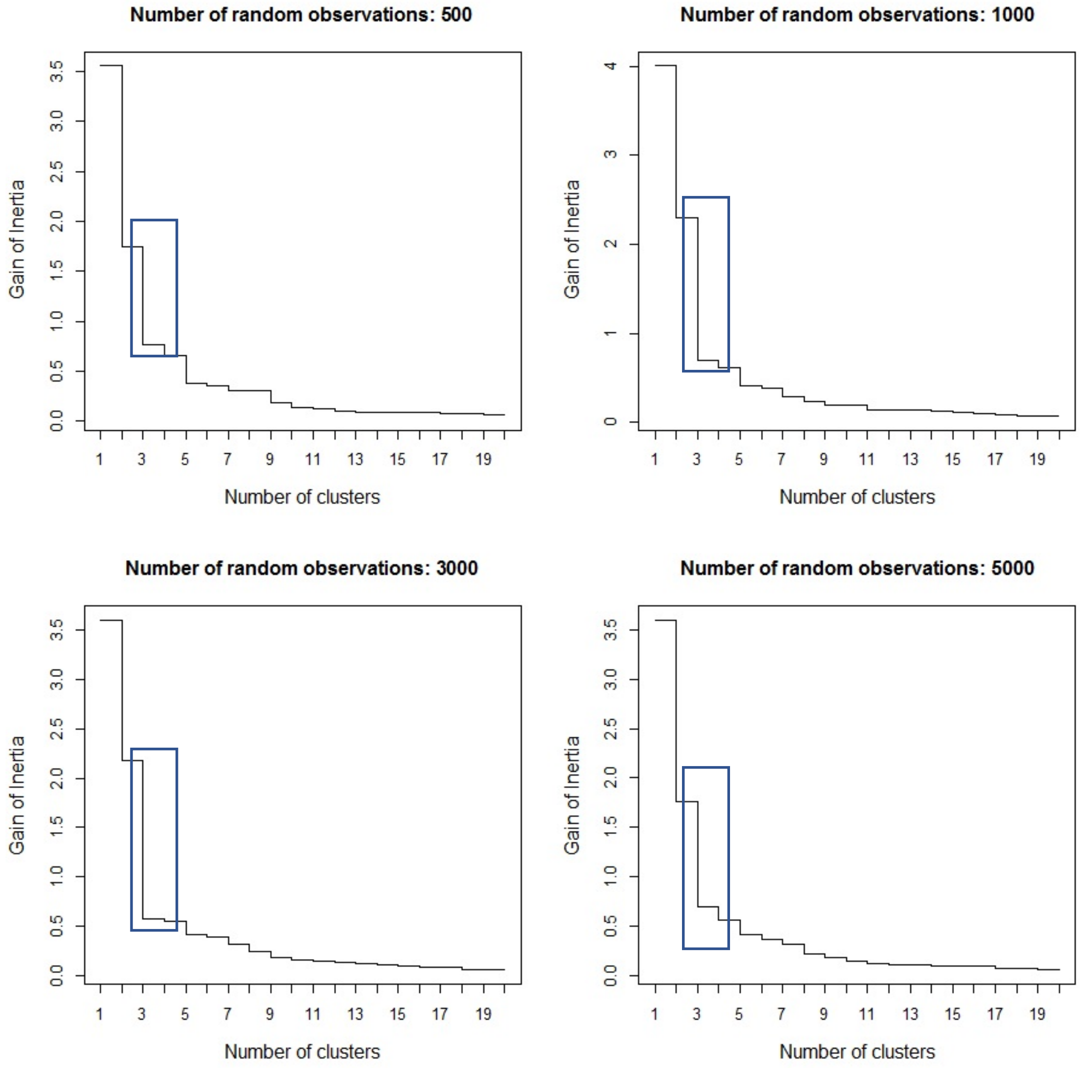

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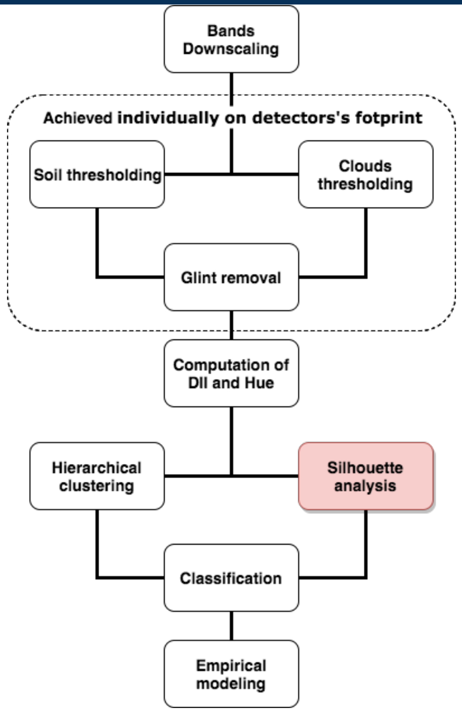
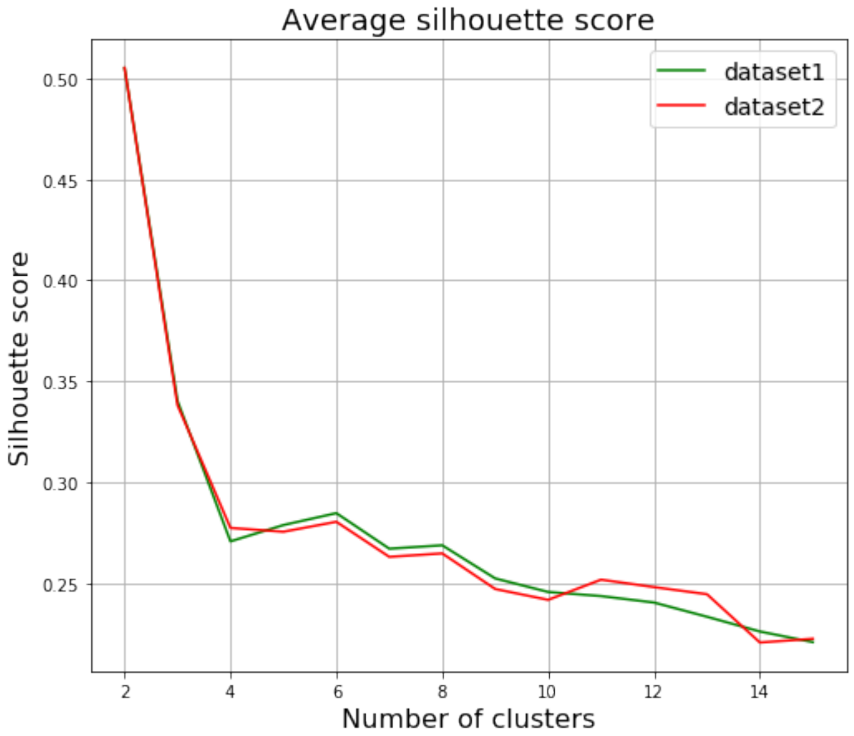
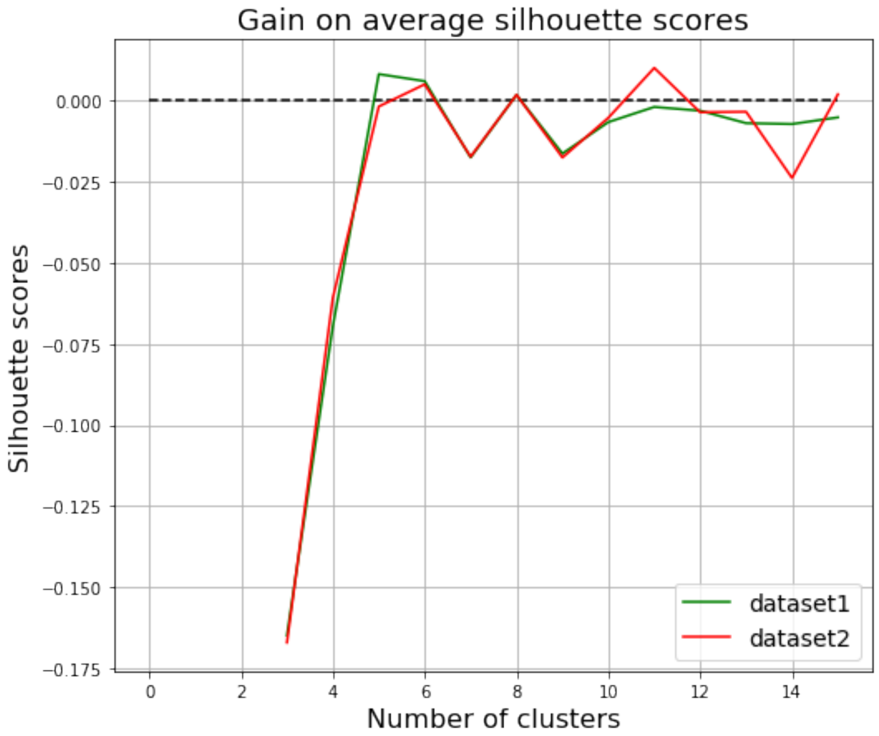


Average Silhouette score





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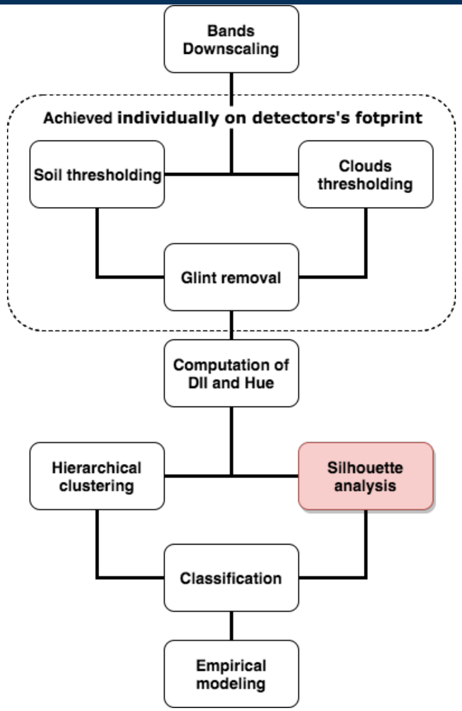

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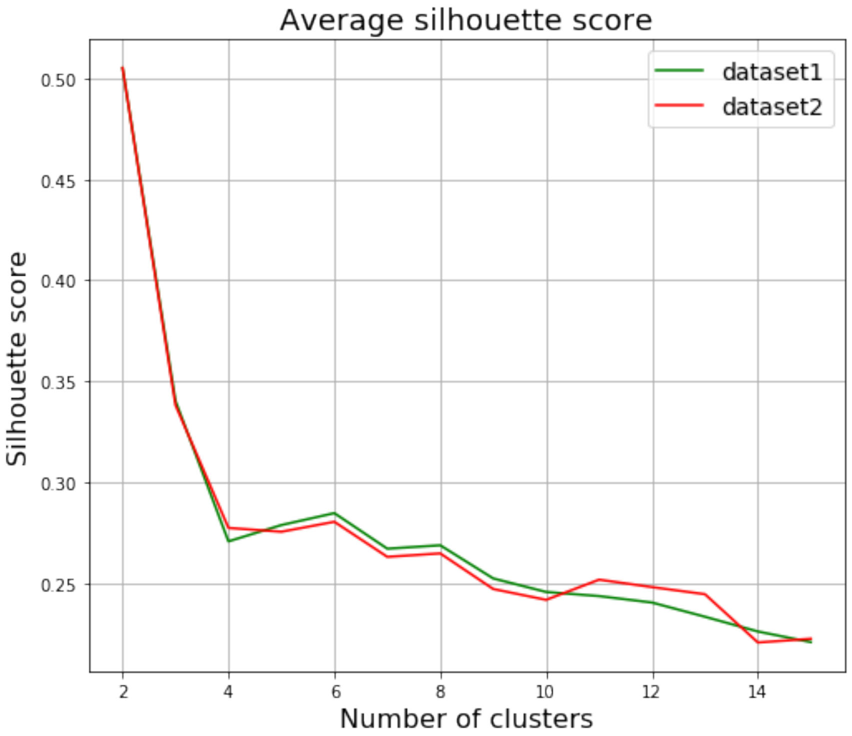
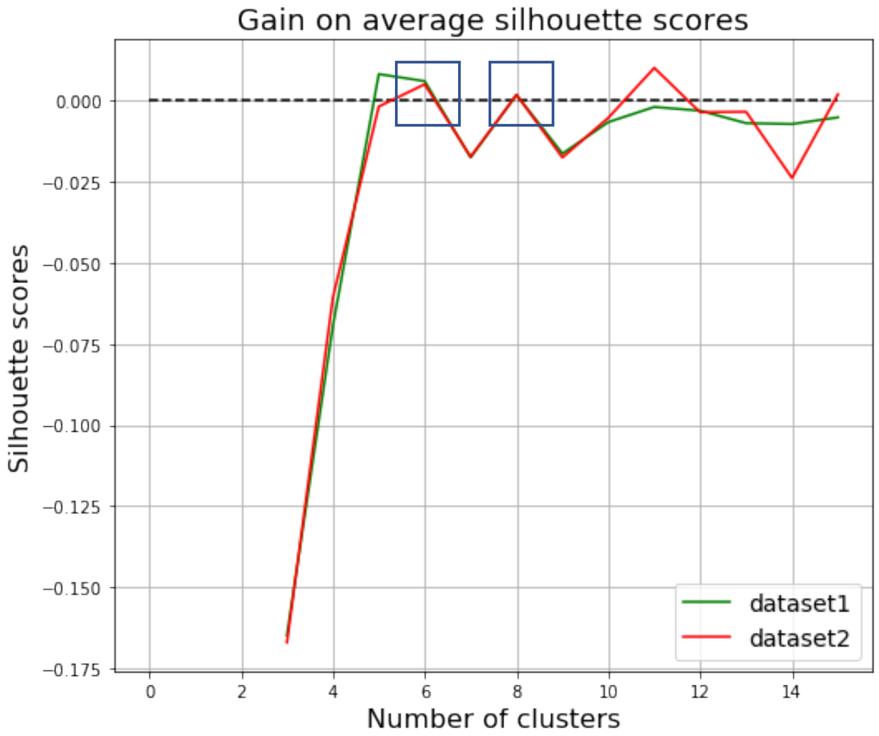
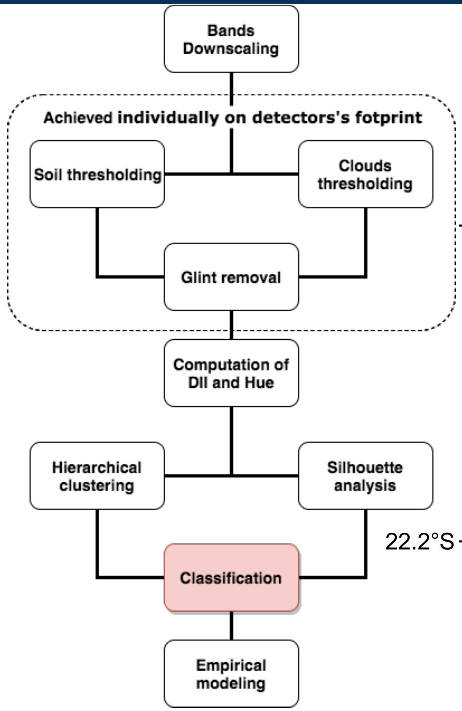
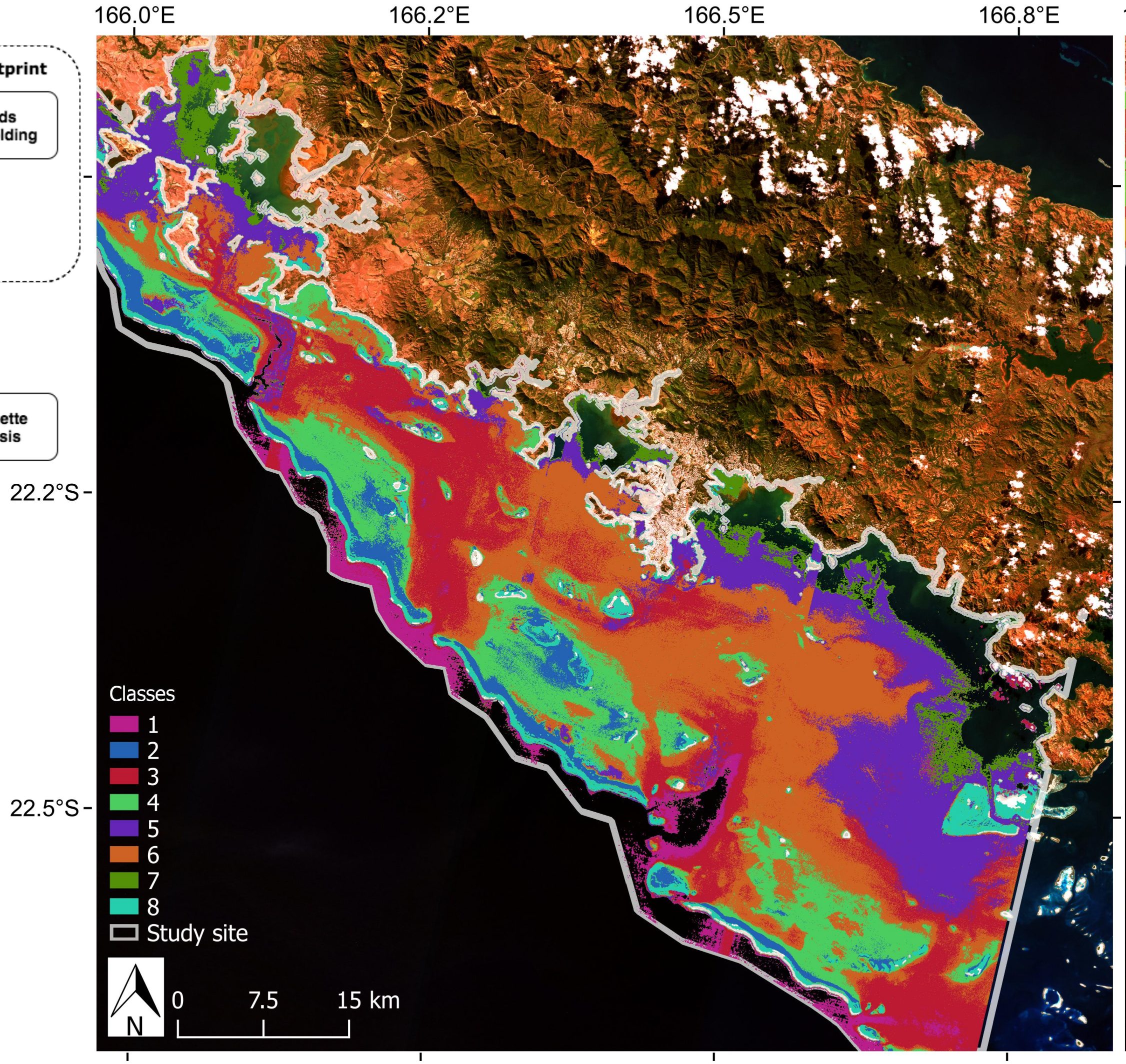
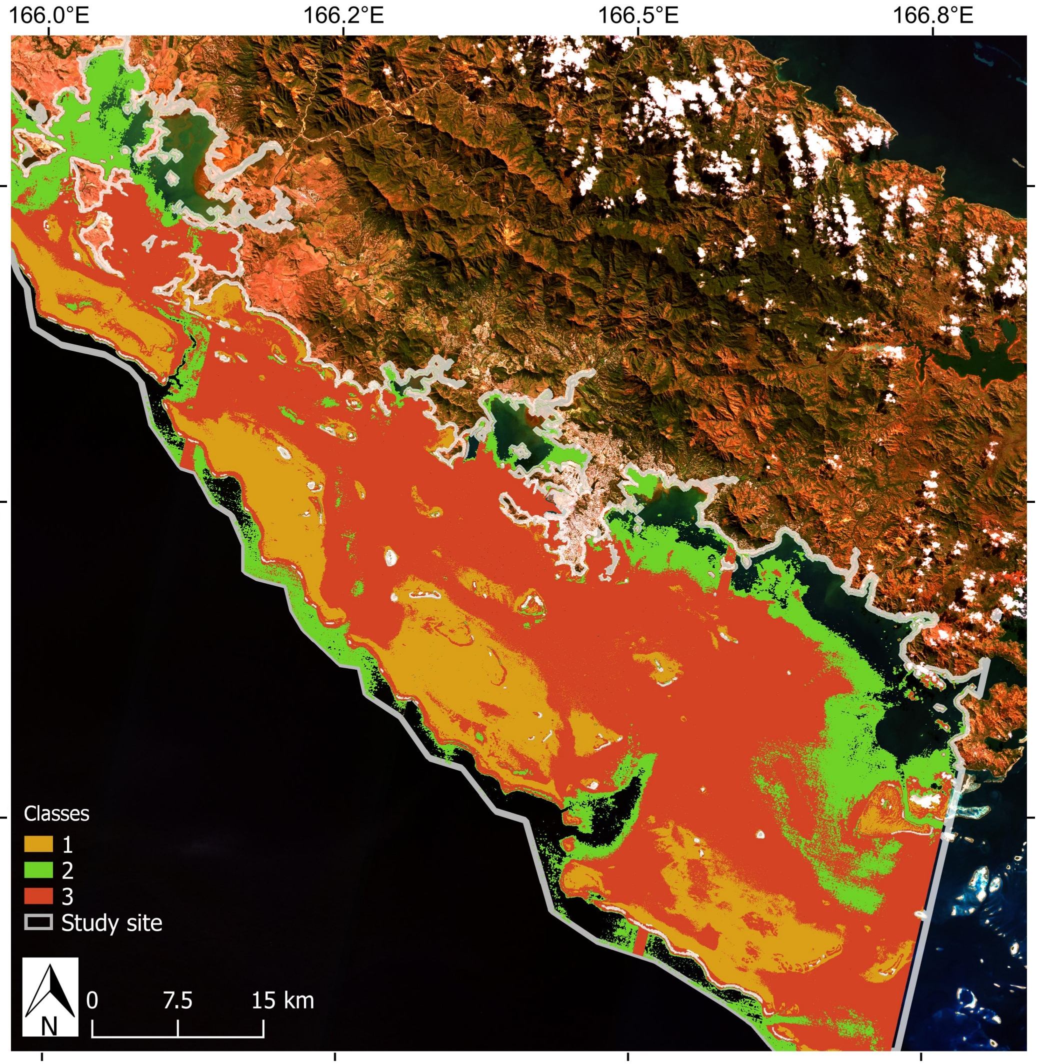




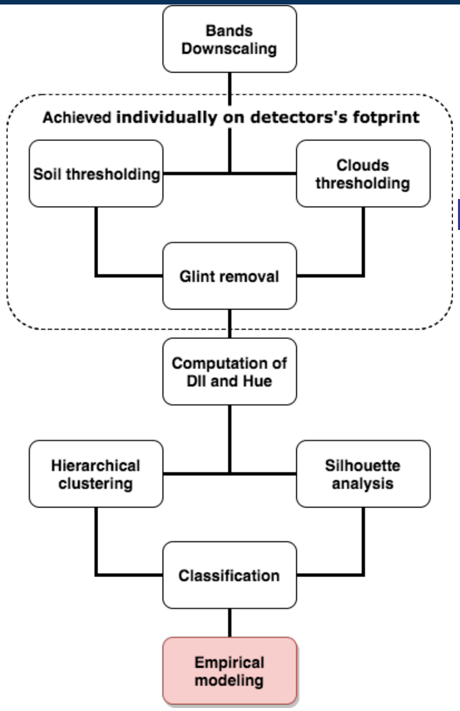
Method and results : K-means classification







Method and results : Empirical modeling



Assumes constant water optical properties

Lyzenga

- Proposes to educe errors driven by variation of bottom reflectance with a linear combination of bands
- relies on the subtraction of the average deep water signal in order to get rid of the volume scattering.
- Litterature :
  - In practice, stability and range of depth of the results is still influenced by variations of environmental parameters.

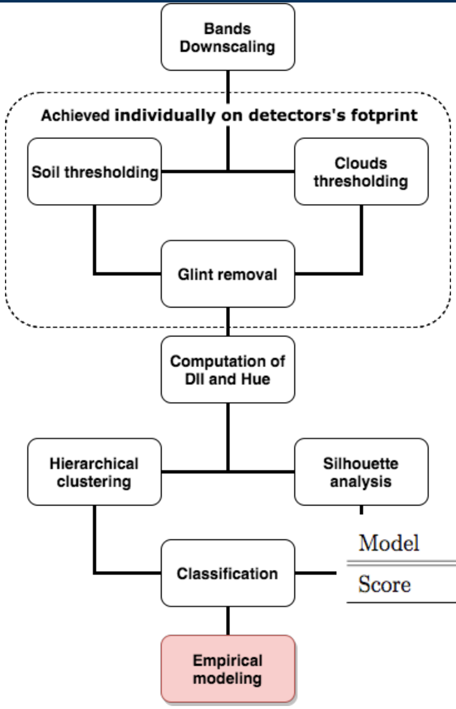
$$Z = h_0 - \sum_{j=1}^{N} h_j \ln(L'_{\lambda j} - L'_{s\lambda j})$$

Stumpf

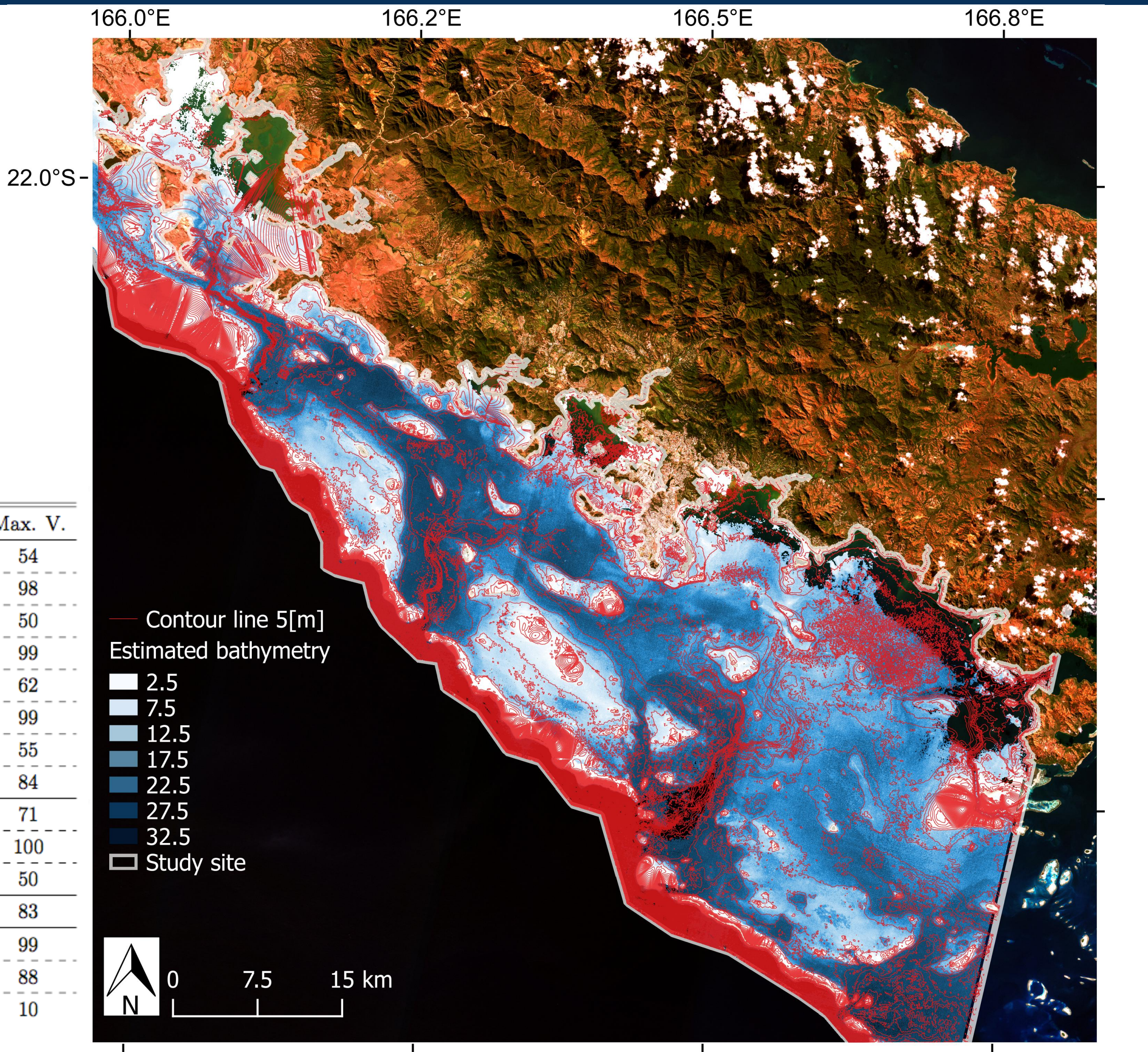
- Relies on the wavelength dependency of the attenuation processes which assumes that ratios of signals undergo stronger variation with depth than with bottom reflectance variation
- Litterature :
  - Should have stabler results with different bottom reflectance
  - Induces additional noises leading to the need a higher ground resolution

$$Z = m_1 \frac{\ln(nL\prime(\lambda_i))}{\ln(nL\prime(\lambda_j))} - m_0$$

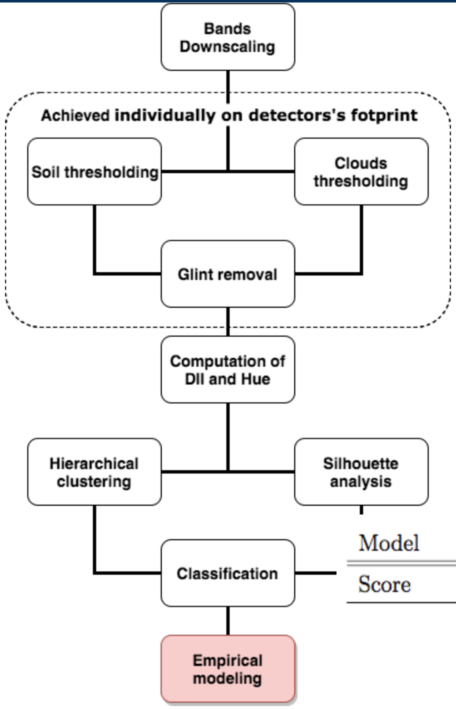
Method and results : Empirical models calibration



Model			Lyzenga				Stumpf			
Score			R^2	Error[m]	Max. D.	Max. V.	R^2	Error[m]	Max. D.	Max. V.
Large site	8 c.	1	0.77	2.4	20	54	0.84	2	20	54
		2	0.80	0.6	10	94	0.78	0.6	10	98
		3	0.37	1.1	20	73	0.27	1.2	20	50
		4	0.85	0.9	20	99	0.82	1	20	99
		5	0.57	2.5	20	10	0.59	2.4	20	62
		6	0.59	1.9	20	10	0.55	1.9	20	99
		7	0.75	3.5	30	55	0.75	3.5	30	55
		8	0.71	2	30	80	0.66	2.2	30	84
	3 c.	1	0.85	0.9	20	71	0.81	1.1	20	71
		2	0.73	1.6	15	10	0.79	2.6	25	100
		3	0.61	1.9	20	50	0.60	2	20	50
	1 c.	-	0.62	2.8	25	96	0.65	1.6	15	83
Small site	3 c.	1	0.83	0.9	15	99	0.80	0.9	15	99
		2	0.80	3	30	100	0.82	3	30	88
		3	0.63	2.1	20	10	0.59	2.6	25	10



Method and results : Empirical models calibration



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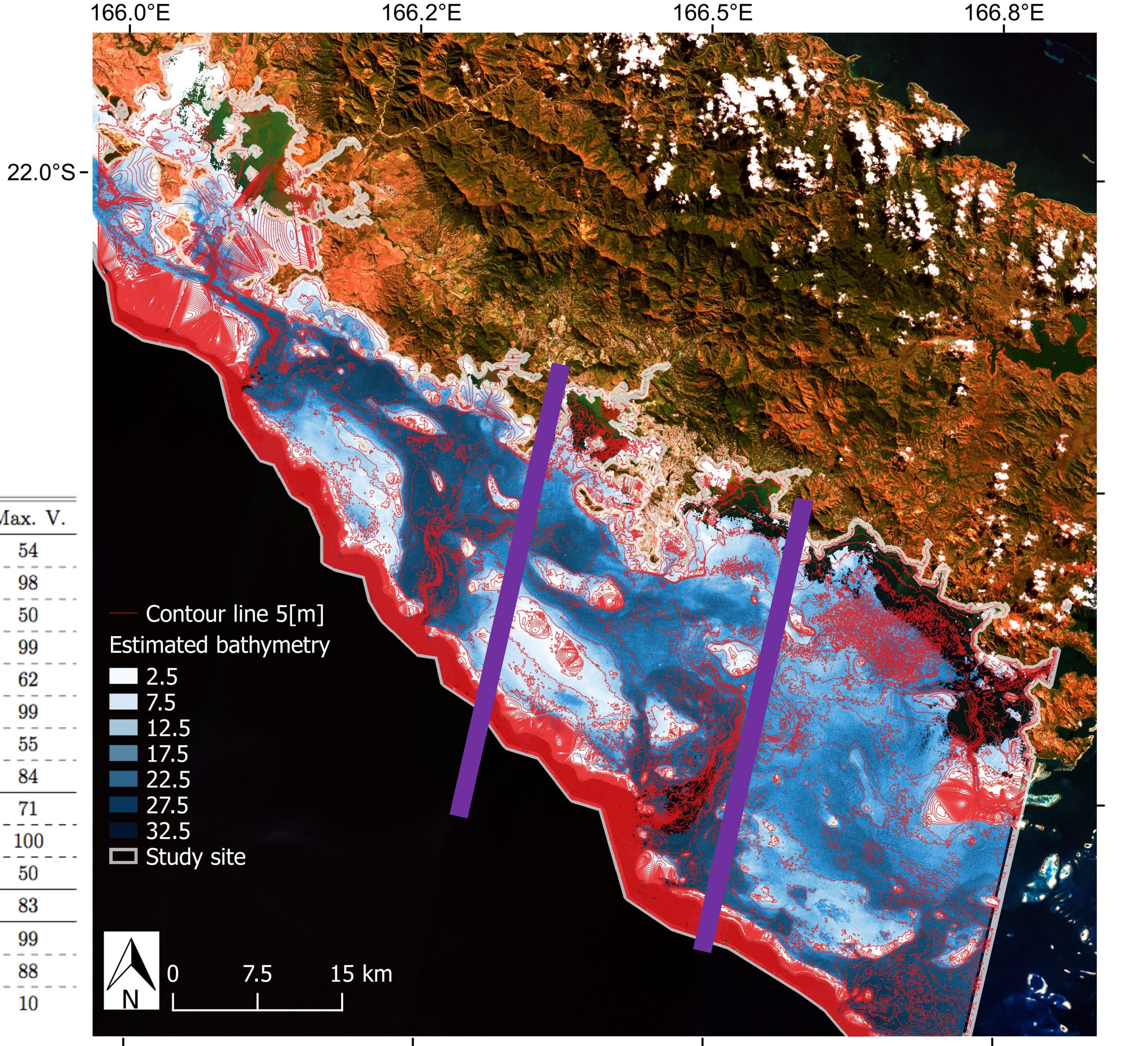
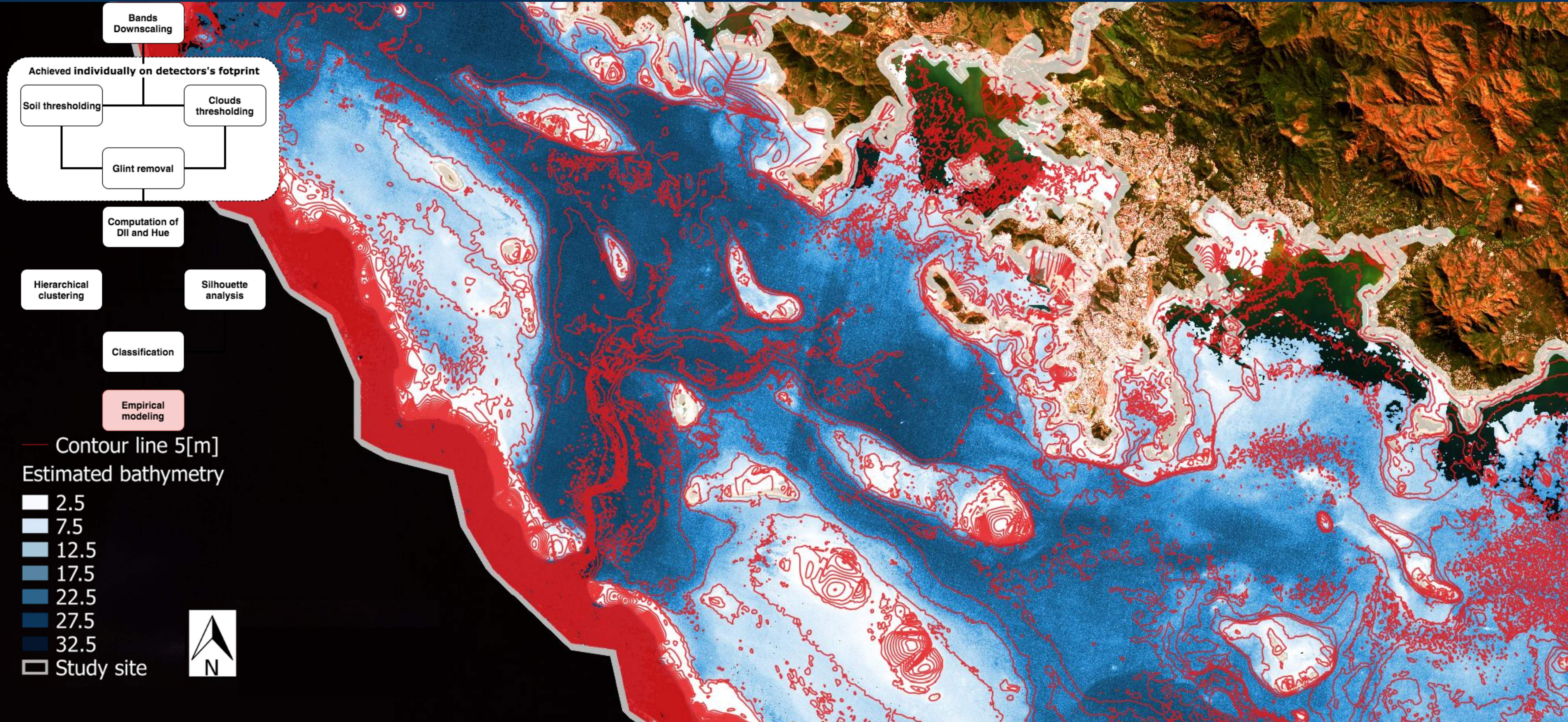


Method and results : Empirical models calibration



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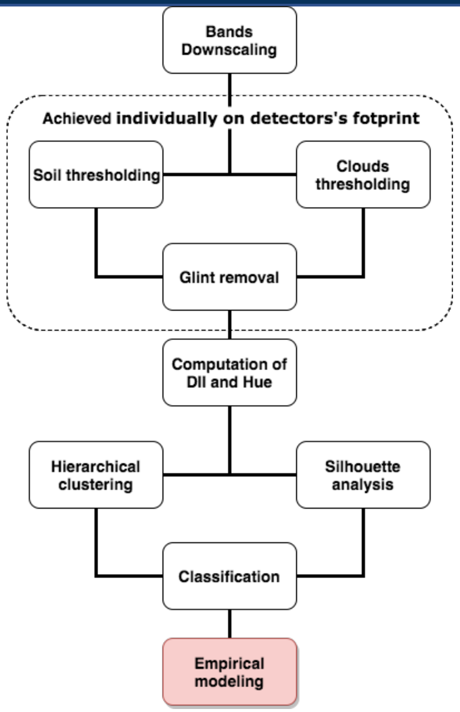

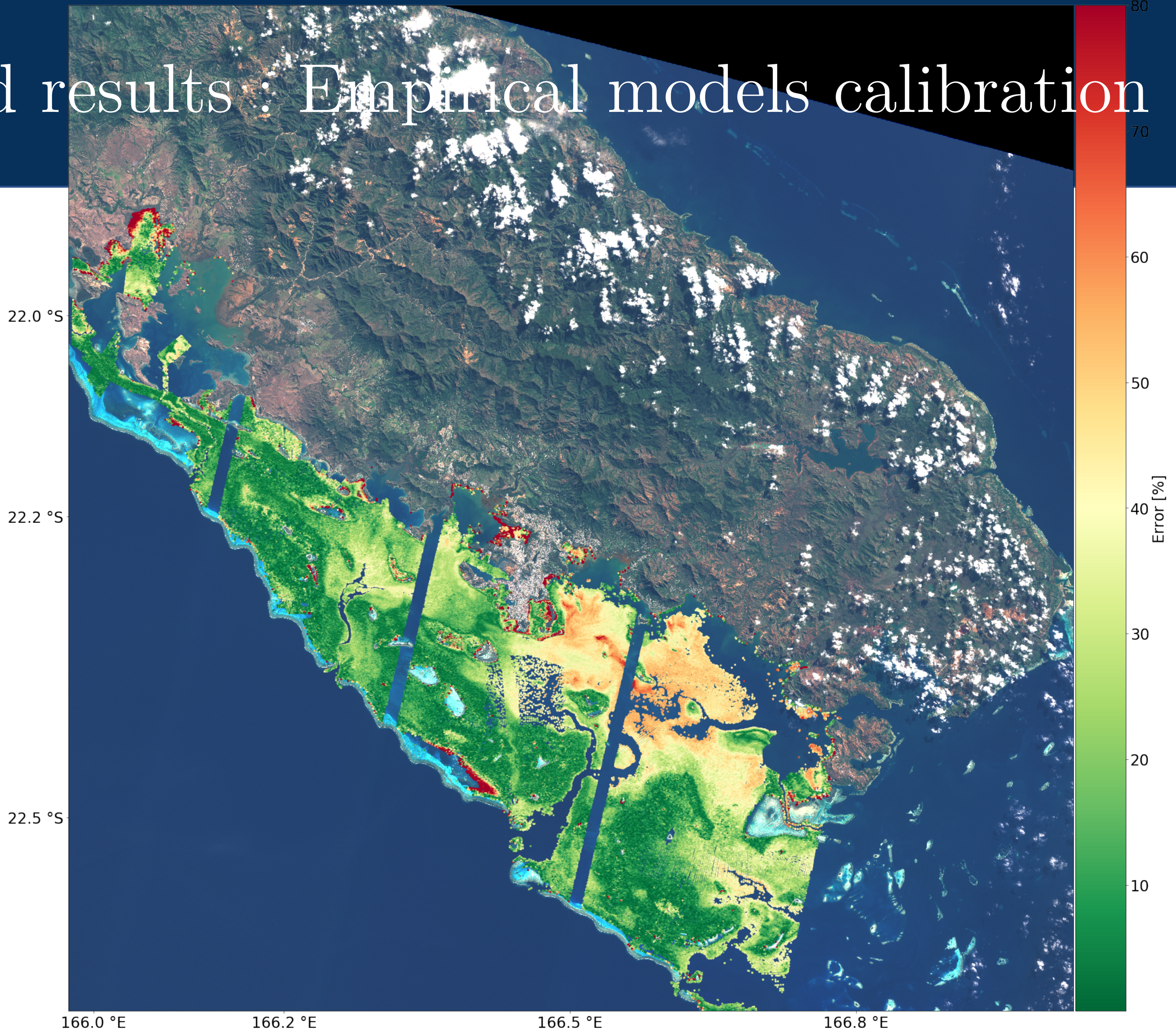

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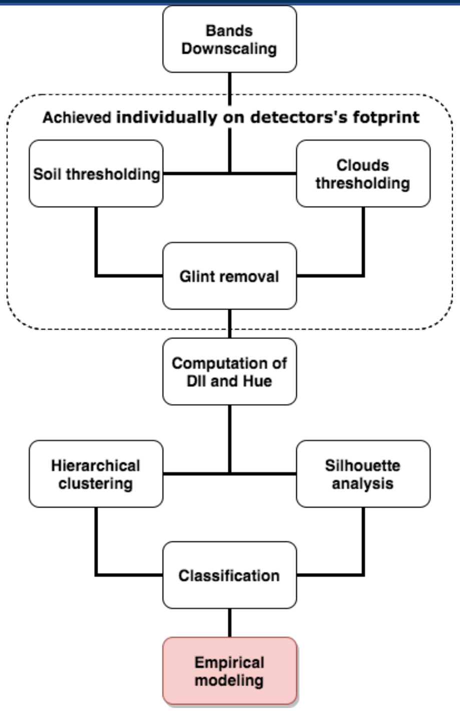

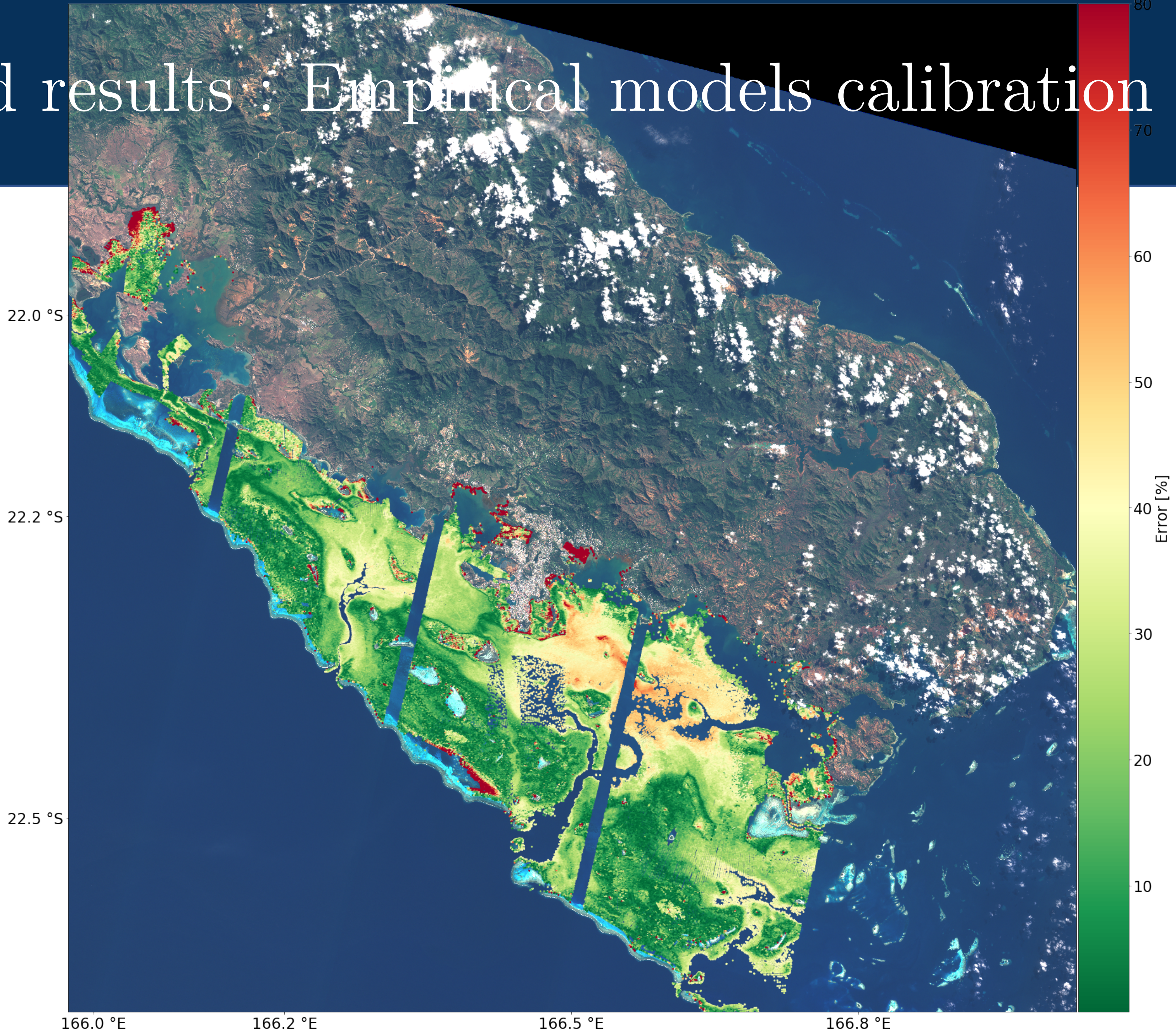

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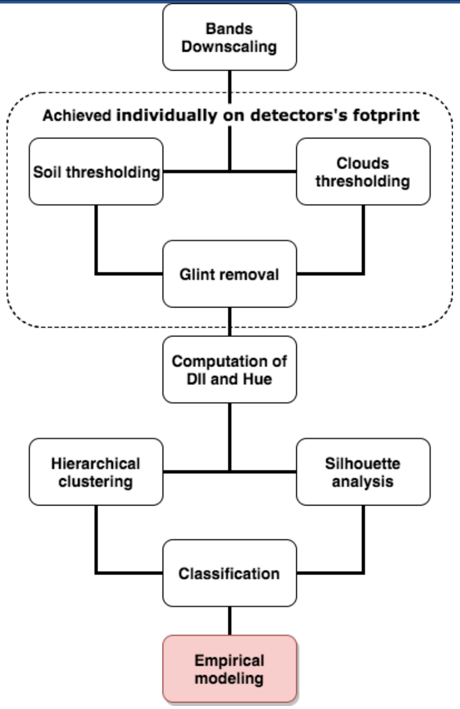
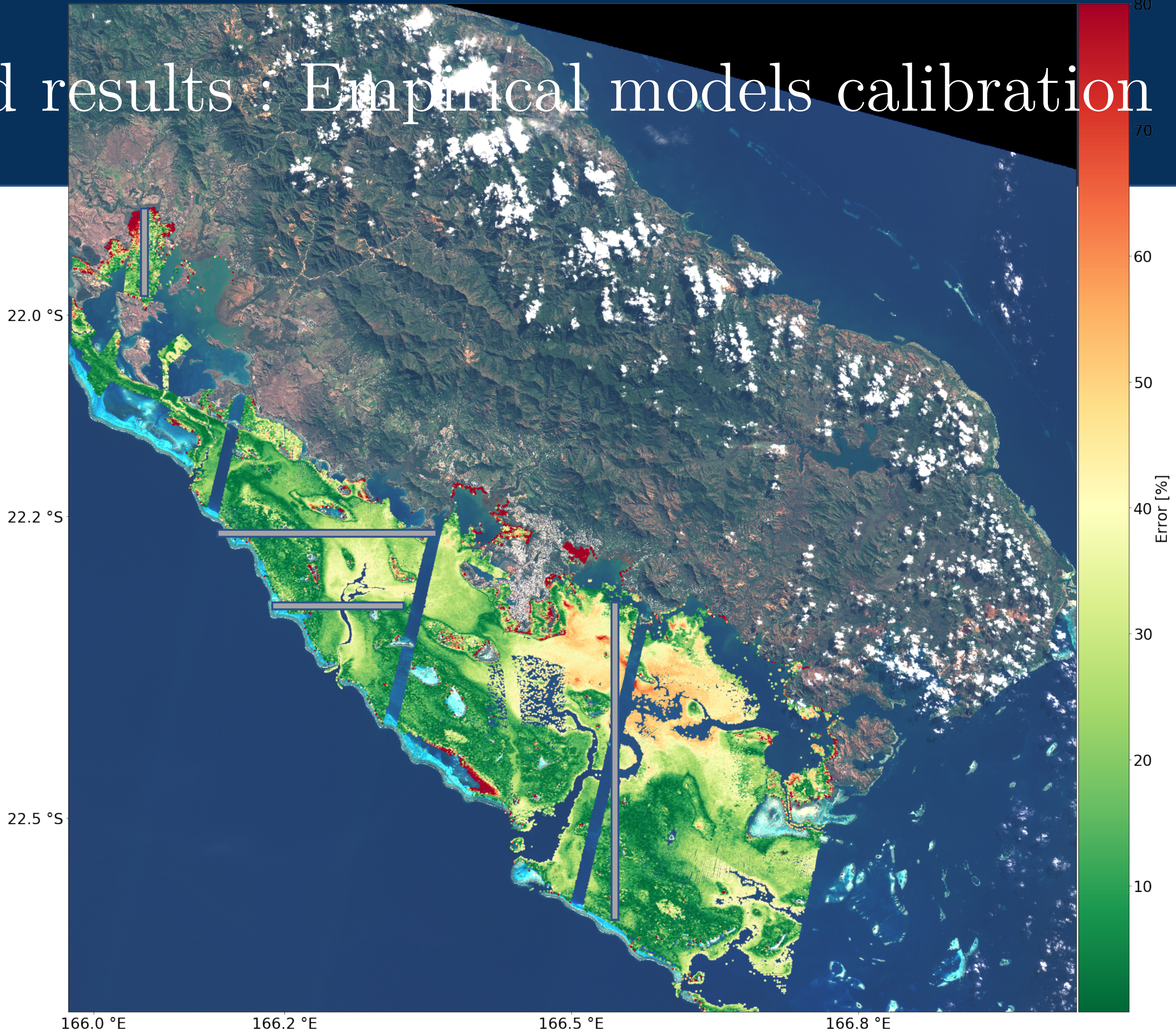
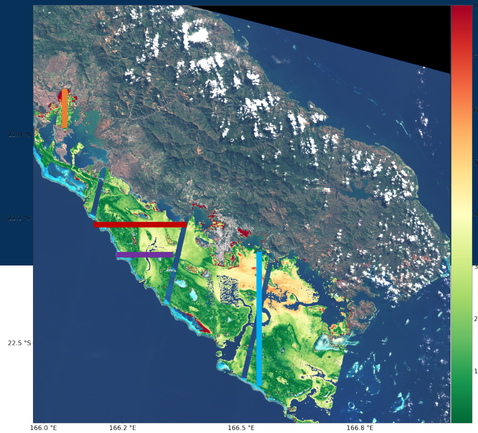
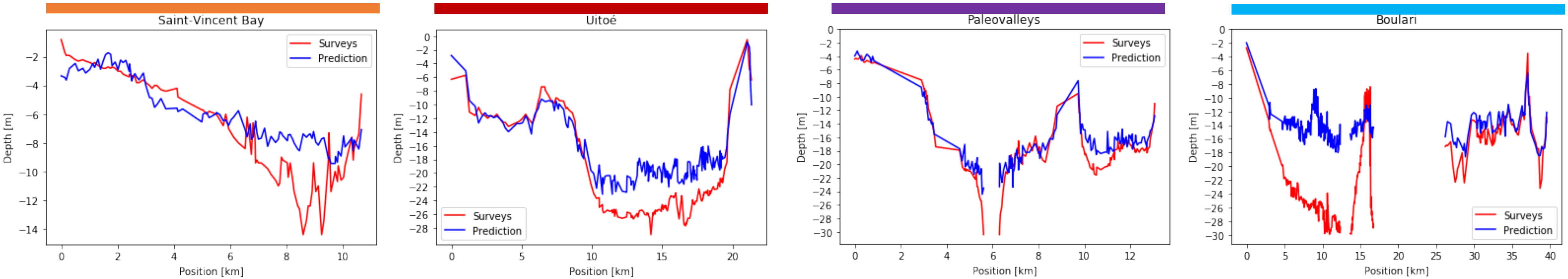




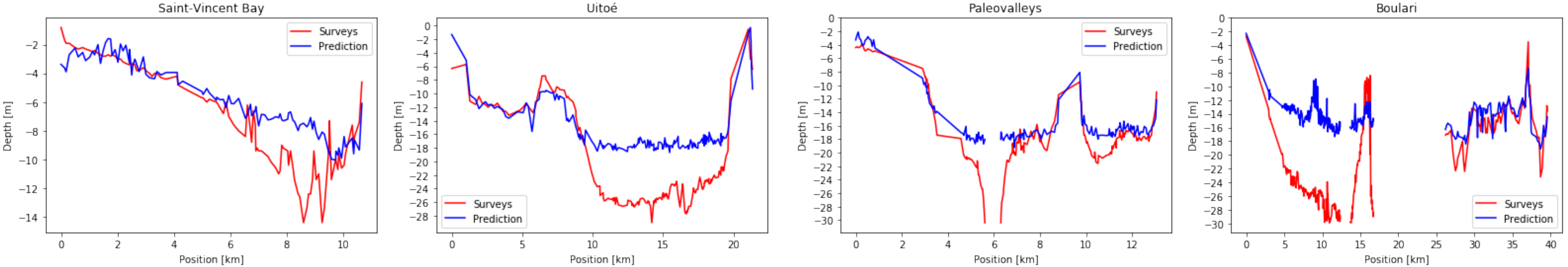
Method and results : Empirical models



Lyzenga: 3 classes



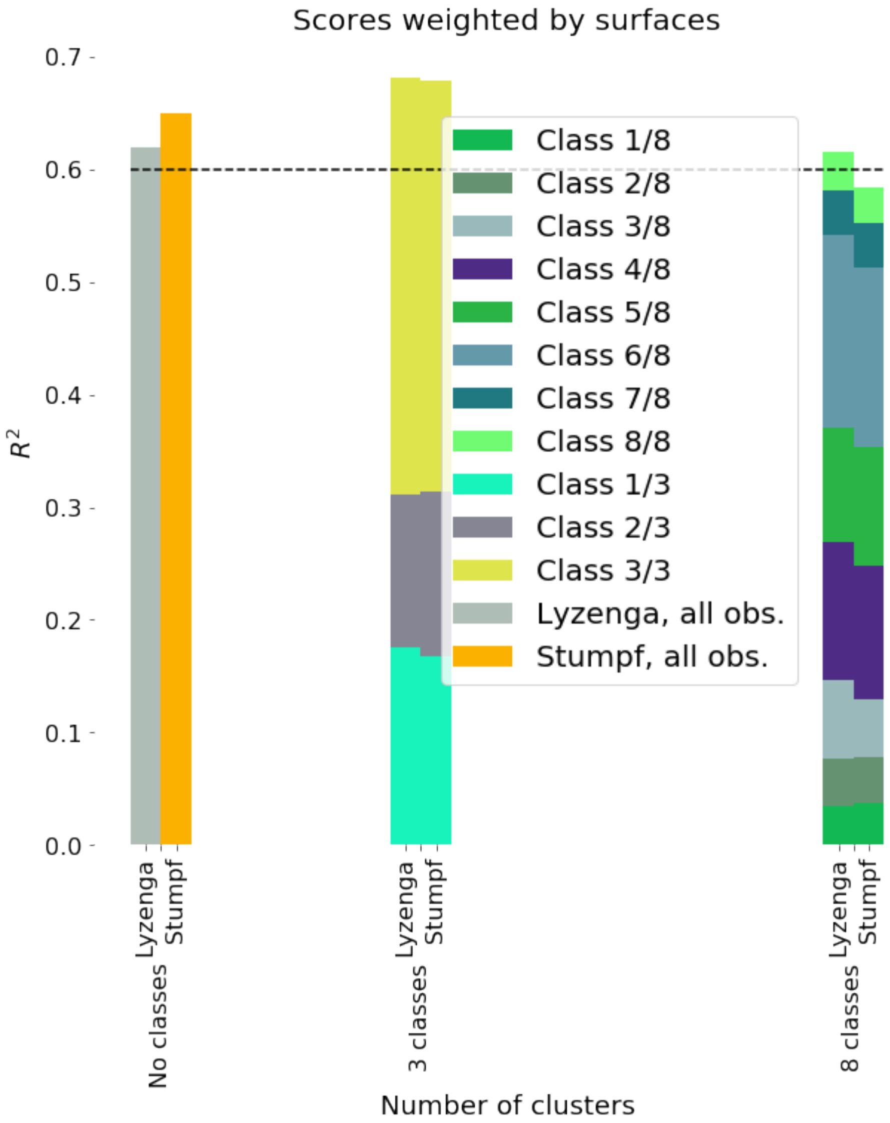
Stumpf: 8 classes



Discussion

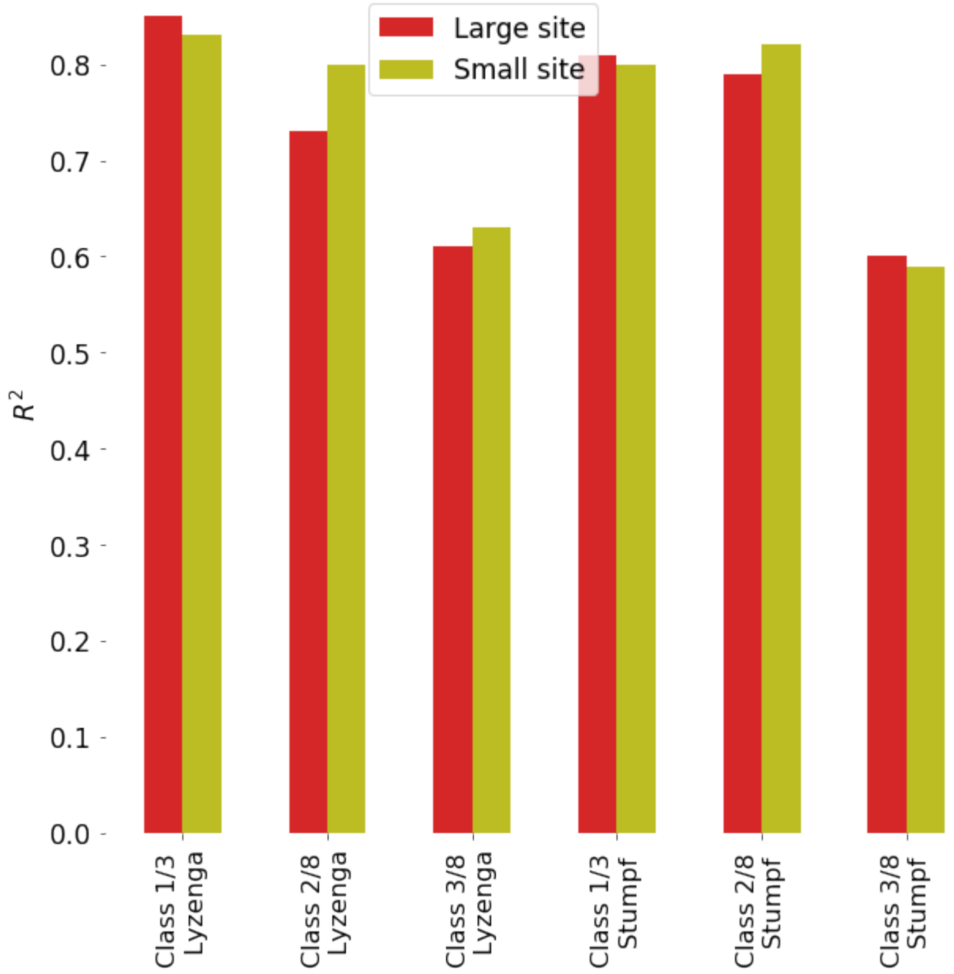
- **Spatial correlation of the errors :areas close to the coasts**

- **A low level clustering, allows an improvement of the precision's performance**



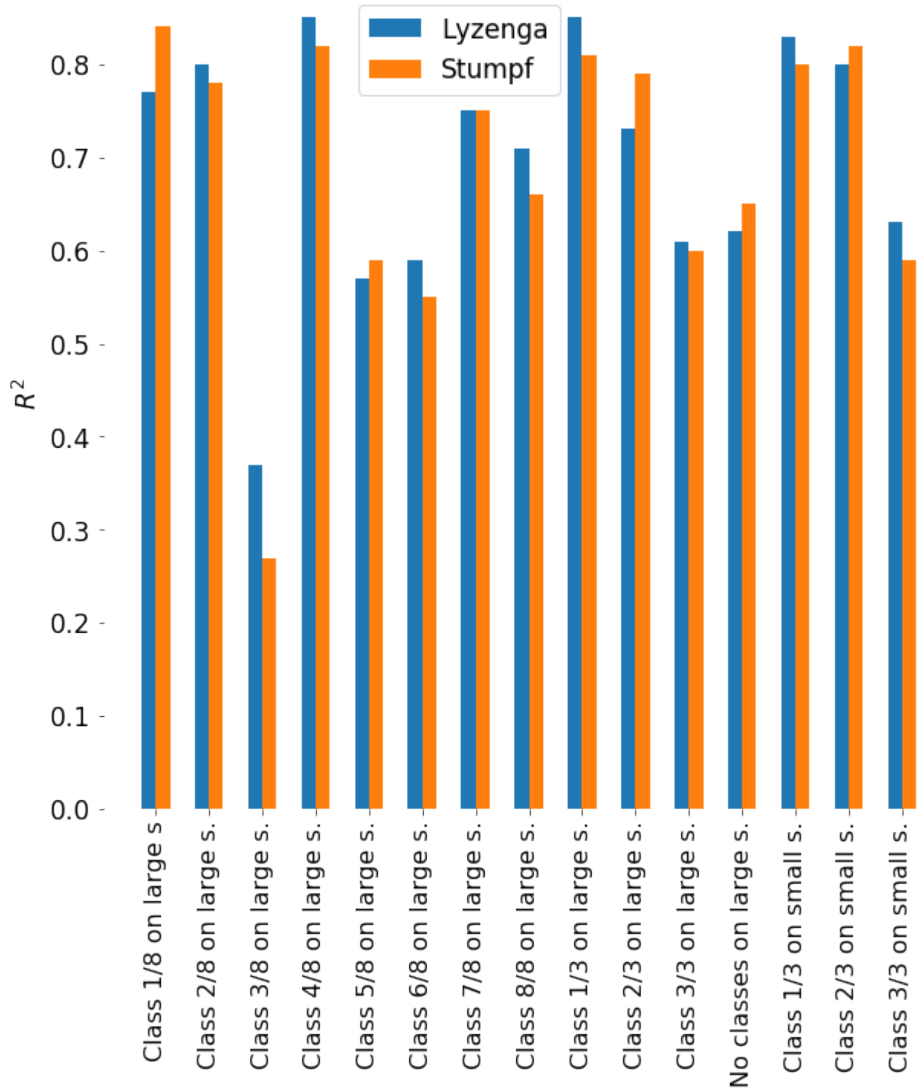
Discussion

- **Spatial correlation of the errors :areas close to the coasts**
- **A low level clustering, allows an improvement of the precision's performance**
- **With a pre-processing achieved individually on detectors' footpring, nothing seems to prevent the application of the empirical methods on a extended area.**



Discussion

- **Spatial correlation of the errors :areas close to the coasts**
- **A low level clustering, allows an improvement of the precision's performance**
- **With a pre-processing achieved individually on detectors' footpring, nothing seems to prevent the application of the empirical methods on a extended area.**
- **Lyzenga's model can be evaluated as slightly better, regarding the precision of the overall models.**



Lyzenga has higher precision 9/15 times

Conclusion

Achieved work

- Sentinel-2 demonstrated its ability to produce SDB
- An approach based on classification as initial has been tested
- Possibility to produce large scale results is shown
- Strong spatial correlation of the errors estimate

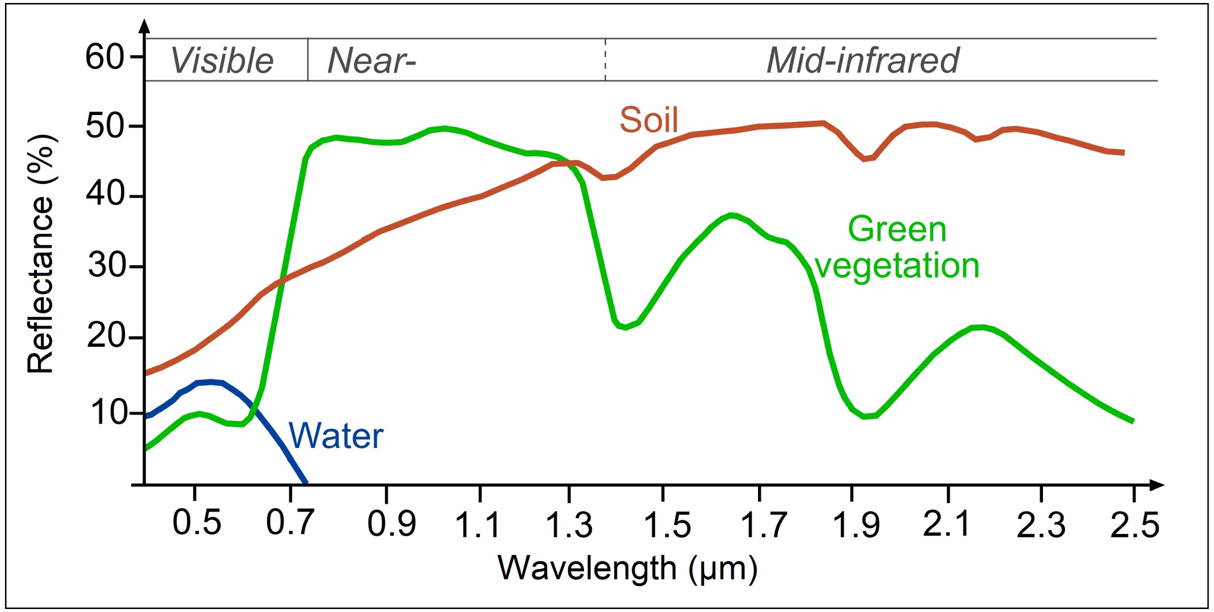
Future work

- The insertion of negative log areas in the classification results and their prediction using Stumpf model
- Realization of in-situ measurments of bottom type in order to create DII
- The merging of Lyzenga's and Stumpf's descriptiors using penalization parameter
- The outliers removal before classification

Image pre-processing

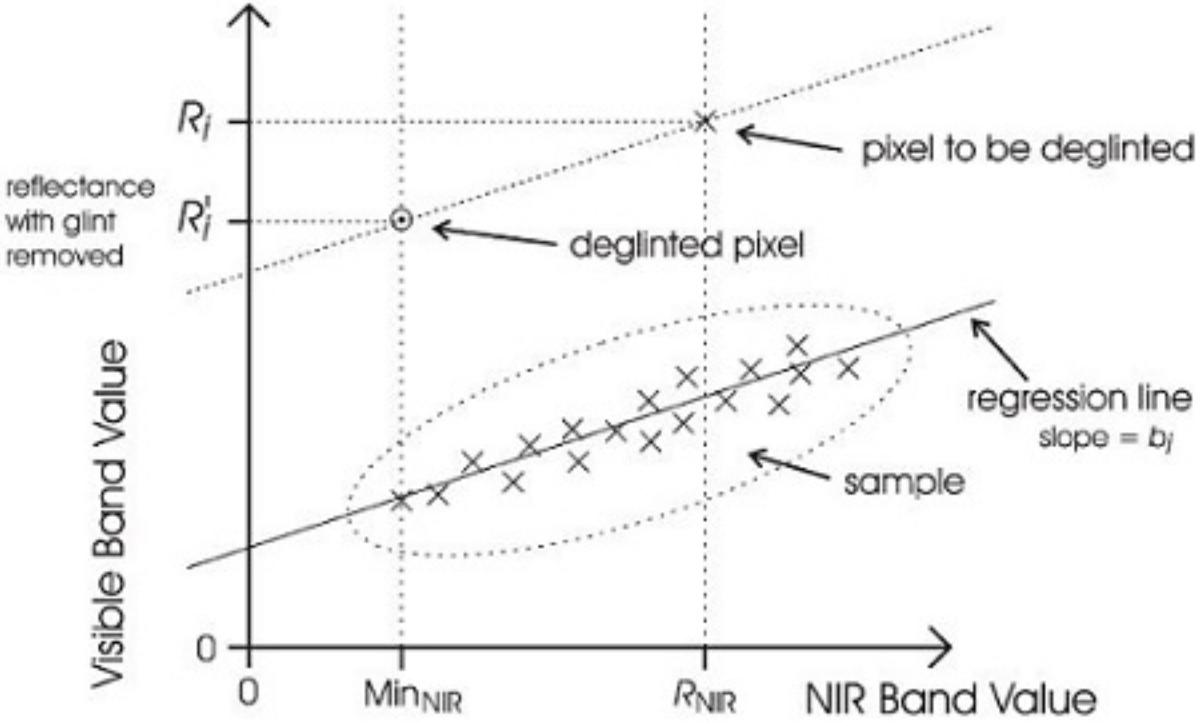
Achieved on individually on detectors' footpring

- **Soil and Clouds thresholding**
  - Threshold chosen by quantile computation following estimation of the ratio of water surface



- **Sun Glint Removal :**

methods of Hedley et al., 2004



$$R_i' = R_i - b_i(R_{\mathrm{NIR}} - \mathrm{Min}_{\mathrm{NIR}})$$

Bottom type and water classification (1)

K-means classifier

- Aims at minimizing within-clusters inertia :

$$I(c, \mu) = \sum_{i=0}^{N} \left\| x^i - \mu_{c^i} \right\|^2$$

1. Initialize K cluster centroids $\mu_{1,}\ \mu_{2,\ldots,}\ \mu_{k,} \in R^d$
2. Iterate until convergence:
   - Every observation is assigned to the closest cluster: $c_i := argmin \parallel x_i - \mu_k \parallel^2$
   - Update the clusters' centroid position : $\mu_k := \frac{\sum_{i=0}^{N} \langle c_{i==k} \rangle x_i}{\sum_{i=0}^{N} \langle c_{i==k} \rangle}$

- **Requires to define the number of clusters**
- **Every descriptors are standardized previously standardized**

The number of clusters

Agglomerative hierarchical clustering

1. Start with each observation as a cluster
2. Until only one cluster remains:
   a) Find the closest pair of clusters.
   b) Merge them.

Ward's method:

- Define a measure of distance between clusters
- aims at minimizing the within-clusters inertia

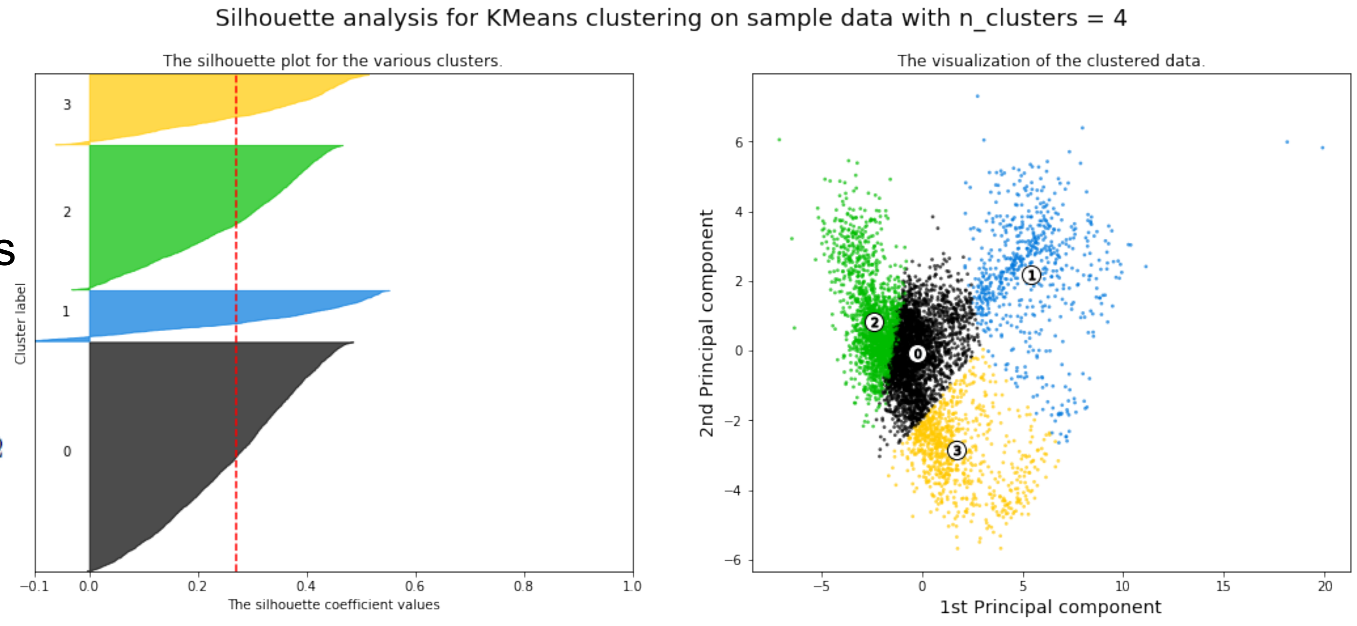
$$\delta(A,B) = \sum_{i \in A \cup B} \left\| x^i_{A,b} - \mu_{A\cup B} \right\|^2 - \sum_{i \in A} \left\| x^i_A - \mu_A \right\|^2 - \sum_{i \in B} \left\| x^i_B - \mu_B \right\|^2 = \frac{n_A n_B}{n_A + n_B} \left\| \mu_A - \mu_B \right\|^2$$

Allows to observe the change in Inertia

Silhouette index

- Define a measure of how well an observation fit in a cluster

$$s(i) = \frac{b(i) - a(i)}{max(b(i), a(i))}$$



Bottom type and water classification (2)

Hue from HSV transformation

- HSV space is commonly used for aerial image classification

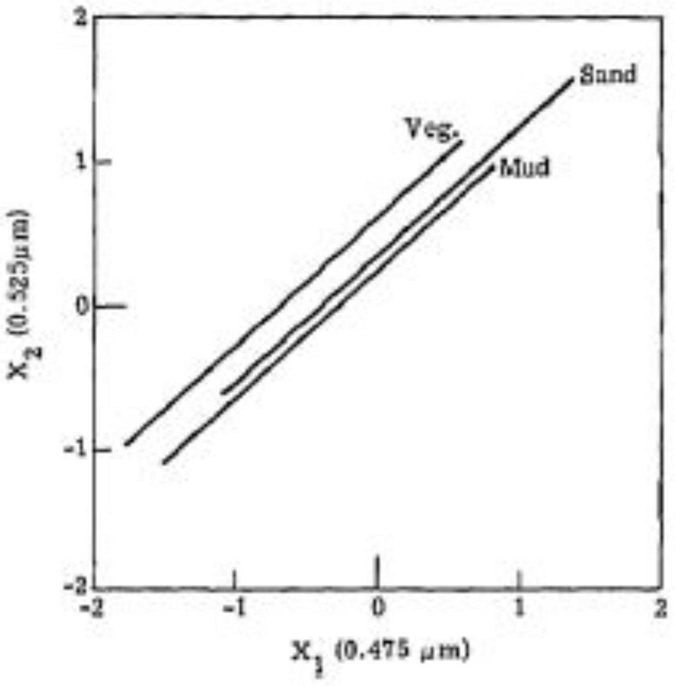
- HSV transformation from a usual Red, Green, Blue space

  to a space formed by three other values:

  The Hue, the value, the saturation

- We made the assumption the Hue is less dependent on radiation attenuation than Red, Green, Blue, Value or Saturation

Depth Invariant Index



$$X_i = \ln(L_i - L_i^{deep})$$

$$X_i = \frac{k_i}{k_j} X_j + d_{ij}$$

$$k_i/k_j = a + \sqrt{a^2 + 1}$$

$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}}$$

$$\sigma_{ij} = \overline{X_i X_j} - (\overline{X_i}\,\overline{X_j})$$

$$d_{ij} = X_i - \frac{k_i}{k_j} X_j$$