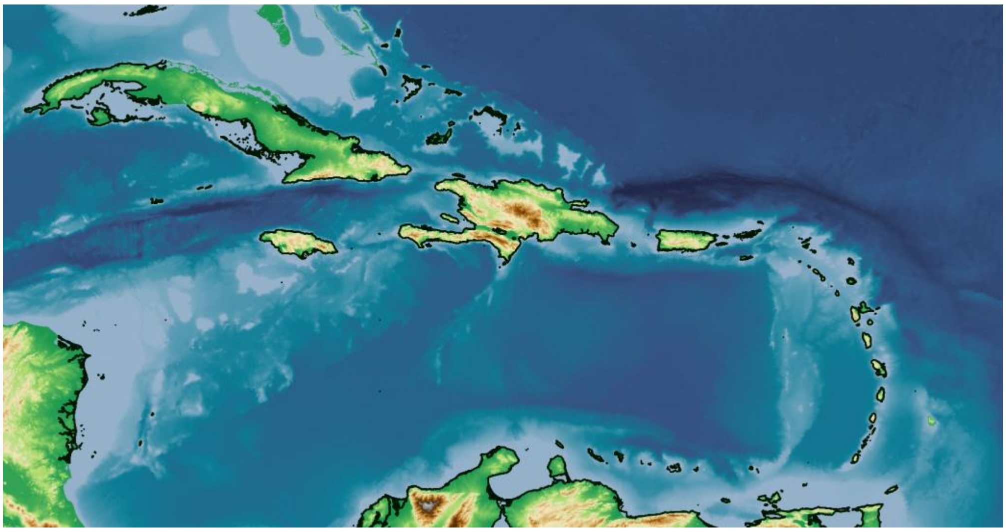
EMODnet Bathymetry

D3.10: Refined best estimate European digital coastlines for a range of vertical levels

Technical Report



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Summary

EMODnet Bathymetry, started in 2009, aims to provide overview and access to available bathymetric datasets and to a harmonised digital bathymetry (DTM) for Europe's sea basins. In 2018, a new set of satellite derived coastlines was added to the products of EMODnet bathymetry. The coastlines are given for the three most commonly used levels, i.e. Lowest Astronomical Tide (LAT), Mean Sea Level (MSL) and Mean High Water (MHW). In addition, the inter-tidal area is derived as the area between the coastlines at MHW and LAT.

In the next release in 2020, the coastlines were much improved, especially for the areas at high latitudes, where poor lighting conditions and snow and ice make detection of the coastline hard. Many corrections were also made, such as the addition of Jan Mayen and Madeira. The second version covers the entire coastline of Europe.

This report now also describes the new 2022 release. The main addition is a new set of coastlines for the Caribbean. This required the additional processing of many satellite images for the Caribbean and the development of tidal levels for the area.

All these coastlines and inter-tidal areas have been added as an extra Bathymetry layer in the EMODnet central map viewer service (https://emodnet.ec.europa.eu/geoviewer/) which allows users to view these and also to download as digital files in shape format. The layers have also been included in the OGC WMS – WFS services[1].

[1] See https://tiles.emodnet-bathymetry.eu for an overview of the EMODnet Bathymetry OGC services

Disclaimer

The EMODnet satellite derived coastline is a high-resolution geography data set (polyline) that must be considered as an estimate of the location of the coastline generated from a methodology involving optical satellite data and tidal modeling. Although the generation of the product has been done with the utmost care, both elements of the methodology might locally generate imprecise results leading to an inaccurate positioning of the resulting coastline.

In consequences as user of this product, you agree that:

- EMODnet Bathymetry does not provide warranties of any kind express or implied, about the completeness, accuracy, reliability, suitability or availability with respect to the information, products, services, or related graphics for any purpose. Any reliance you place on such information is therefore strictly at your own risk.

- In no event will EMODnet Bathymetry be liable for any loss or damage of any sorts arising from the use of this data and derivatives.

- The provided coastlines datasets do not serve as replacement of official coastlines as produced by the responsible national authorities. They should not be used where official coastlines are required.

Introduction

A coastline is a delineation materialised by a curve that separates the land from the sea. Since, the sea-level changes over time through tides and the weather, the instantaneous coastline also changes continuously. For many applications it is more practical to use the coastline at high-water, since this quantity is more stable and it reflects roughly what many people intuitively would consider the coastline. There are many different definitions of high-water but is common practice to use Mean High Water for this purpose. On the other hand, for territorial claims, it is more common to base these on low water. For this purpose, it is common to use Lowest Astronomical Tides (LAT) (United Nations Convention on the Law of the Sea, 1994). To stay close to common practice, this report and the derived products will adhere to these conventions. This will also facilitate the comparison to other datasets. It should be noted that the term 'coastlines' is often used in a specific context where there are legal implications, in this context one implicitly refers to the official datasets as produced by the authorities. The datasets described here should not be used for this purpose. On the other hand, the satellite derived coastline described in this report uses a single methodology everywhere, ensuring a uniform generation of this product across Europe and thus can be used to compare with other coastline data. In addition, it can be useful where no other high-resolution coastline is available. Moreover, this methodology benefits from the fact that satellites revisit the same area frequently (e.g. sentinel 2 has a revisit frequency of around 2 days on average) allowing for frequent updates (in case of coastal erosion or anthropic effects) and for detection of tidal influences.

Figure 1 Example of coastlines at low-water, mean sea-level and high-water near Scheveningen in the Netherlands

This document describes the work related to satellite derived coastline that has been carried out within the EMODnet Bathymetry projects. The first part of the document describes the methodology for coastline retrieval. The following section presents the tidal correction methodology. Finally, the results and the conclusions are presented.

Methods

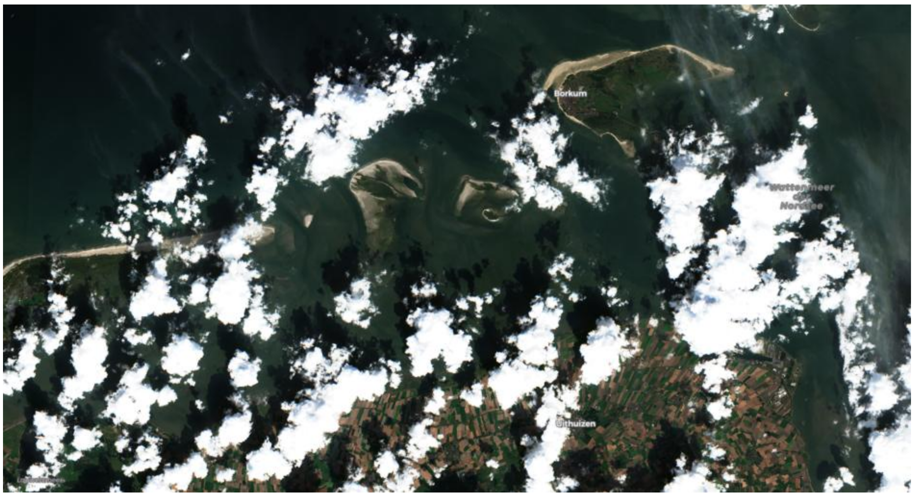
The identification of a “coastline” involves two general stages: the first requires the selection and definition of a coastline indicator feature, and the second is the detection of the chosen coastline feature within the available data source. To date, there are different techniques and algorithms for coastline detection. Recent photogrammetry, topographic data collection, and digital image-processing techniques now make it possible for the coastal investigator to use objective coastline detection methods. Some of the methods to be explored further are presented below.

Surface water detection from multispectral images

Existing methods for surface water detection from multispectral satellite data use the fact that water significantly absorbs most radiation at near-infrared wavelengths and beyond. This fact makes it easy to detect clear water employing spectral indices, such as the Normalized Difference Water Index (NDWI), McFeeters (1996).

$$NDWI = \frac{\rho_{green} - \rho_{nir}}{\rho_{green} + \rho_{nir}}$$

where ρ_{green} and ρ_{nir} correspond to the spectral reflectance of green and near-infrared bands. By design, the index values (similar to normalized difference vegetation index (Rouse Jr et al. (1974)) vary between -1 and 1, with water appearing mostly when the index value is greater than zero.



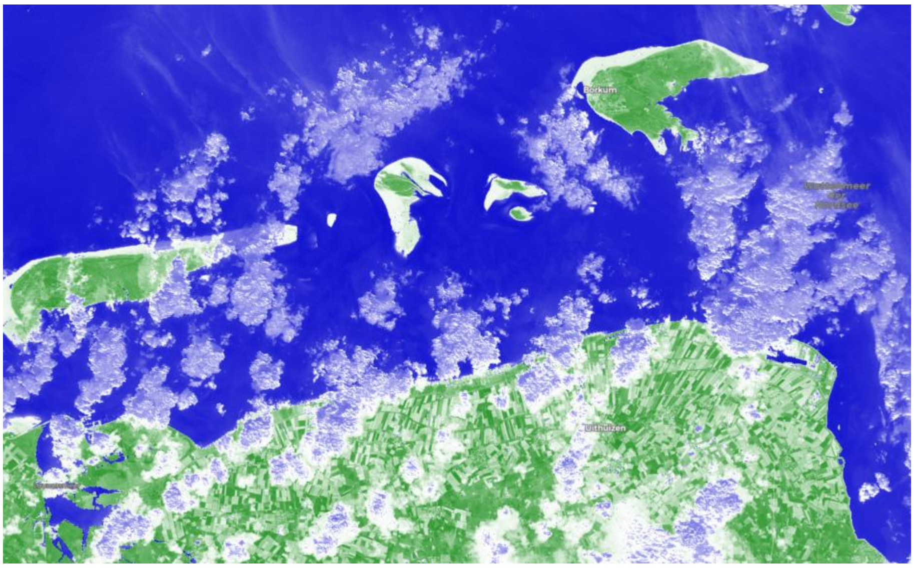


Figure 2 Level 2 True color and NDWI images from Sentinel 2 on August 18th 2020 for Wadden Islands around Borkum in Germany

NDWI has been used to distinguish between land and water (Bayram et al, 2008; Kuleli et al, 2011; Almonacid-Caballer et al, 2016) and, hence, detect the coastline from satellite images. This technique was used for example in Donchyts et al. (2016) to study changes in land cover worldwide. The availability of Landsat satellite imagery allows us to study these coastlines from 1984 until now with a pixel resolution 15 to 30m. The recent Sentinel-2 satellite mission (ESA, 2016) even go up to a pixel resolution of 10m. Based on these images historic trends in coastal erosion can be detected. Several publication report on changes to coastlines, eg Luijendijk et al 2018. Similar analyses can be made to derive other coastal parameters such as vegetation (FAST, 2017), sand and human infrastructure.

Here, the NDWI algorithm is used to derive coastlines for the European waters and the Carribean, this in combination with a tidal model allows, to retrieved coastlines at different vertical datum (e.g. MSL, MHW, LAT).

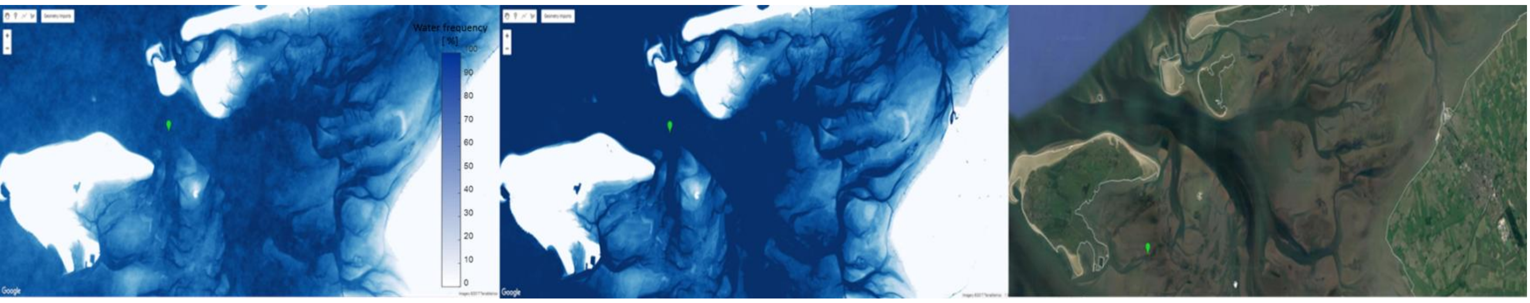


Figure 3 Water occurrence estimated from Landsat 8 and Sentinel-2 images around Wadden Island Borkum (Germany), the first image shows the water occurrence computed as a simple mean NDWI value from all images, the second image shows water occurrence estimate using statistical cloud removal method, and the third image the MHW coastline retrieved from water occurrence.

Method for the coastline estimation from optical satellite images

While a single satellite image can be used to detect coastline geometry, a much more robust approach is to combine many satellite images. This allows capturing not only coastline geometry, but also variations in the coastline geometry due to tidal water level changes. Several methods have been proposed to capture this variation in order to derive inter-tidal bathymetry (Sagar, 2017).

Processing of satellite images at large spatial and temporal scales is a computationally task, due to large volumes of satellite data to be processed, but also, due to variety in the satellite data radiometric properties and formats. In this project, we have used Google Earth Engine platform (Gorelick, 2018) to overcome some of these challenges. The platform allows parallel processing of huge volumes of satellite data in reasonable time and harmonizes satellite data acquired by different satellite missions performed by NASA and ESA. In this project, we have used a mixture of top-of-atmosphere reflectance satellite images from NASA/USGS Landsat 8 and ESA Sentinel-2 satellite missions, acquired during 2013-2020.

Automated detection of surface water from multispectral satellite images using passive sensor has received significant attention in recent years, Donchyts, 2016 (a), (b)., Pekel, 2016. A number of algorithms were developed to make surface water detection fully automatic. The main sources of noise for optical images are:

a) Clouds and cloud shadows
b) Shadows due to topographic effects
c) Atmospheric effects (scattering, aerosols)
d) Urban areas (complex spectral signal resulting in false-positive surface water)
e) Snow and ice
f) Systematic errors (georeferencing and georectification, sensor hardware of software errors, limited radiometric resolution)
g) Variable thresholds for land/water discrimination when using classical NDWI spectral index
h) Coastline with a very dynamic morphological changes

To address most of these challenges, we have used statistical methods to process and combine many satellite images. In particular, instead of detecting surface water from satellite images using fixed NDWI threshold, the images were processed to represent a probability of land/water boundary, a values close to 1 indicates that a particular pixel is always "wet", therefore almost sure that location is water. The algorithm shown in 3 was used to process most images from Landsat 8 and Sentinel-2 missions covering EMODnet project area.

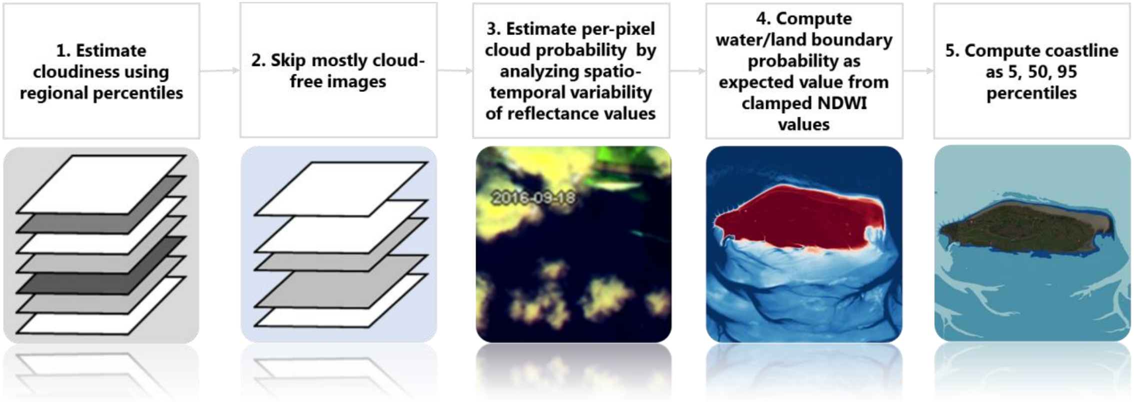


Figure 4 Processing pipeline for coastline detection from optical satellite images, capturing intertidal water level changes

Instead of performing a direct cloud masking for every image, our algorithm fist "learns" the overall distribution of reflectance values within observed over every pixel as the first step. Then, a cloudiness metric is introduced for every image covering the area where potential coastline boundary is expected to be located. This metric is then used to filter-out images mostly covered by clouds. Then, a more robust per-pixel cloudiness probability is computed by comparing its values with the spatio-temporal distribution with a small neighbourhood around every pixel. The resulting cloudiness probability is used to estimate the final water occurrence, computed as the weighted average, using cloudiness as weights. The final water occurrence is used to estimate the coastline geometries.

After assigning cloudiness metric for every image (patch/tile), the algorithm uses mean cloud frequency estimated by Wilson, 2016 to determine the number of images to skip, significantly reducing noise in the resulting time series, 4. For northern regions (The Netherlands, UK, Germany, Sweden, Finland), the mean cloud frequency is relatively high (~60-80%), resulting in only a fraction of satellite images can be used for processing. While this can be an issue for the analysis covering short periods, we were able to overcome this using all of the available images acquired during 2013-2020.

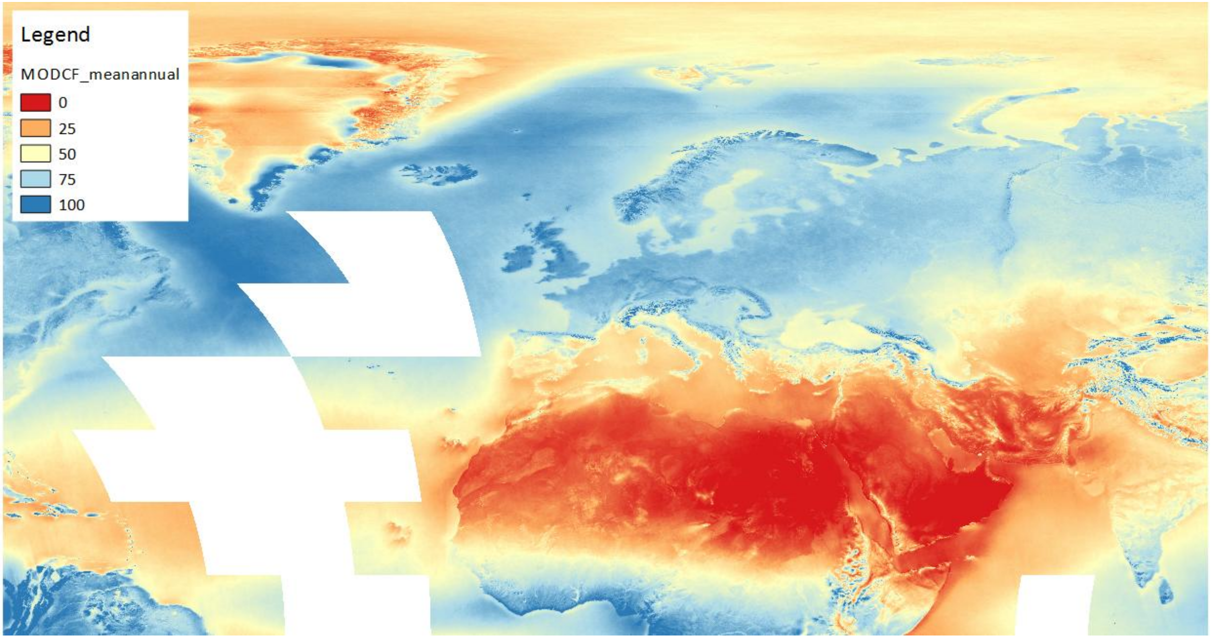


Figure 5 Cloud frequency (0-100) used during step 2 of the algorithm

The 6 shows an example of the final water occurrence estimated using the method outlined above. This spatial resolution of this water occurrence varies between 10m and 30m, depending on the number of Sentinel-2 and Landsat 8 images available for a given area and cloud conditions.

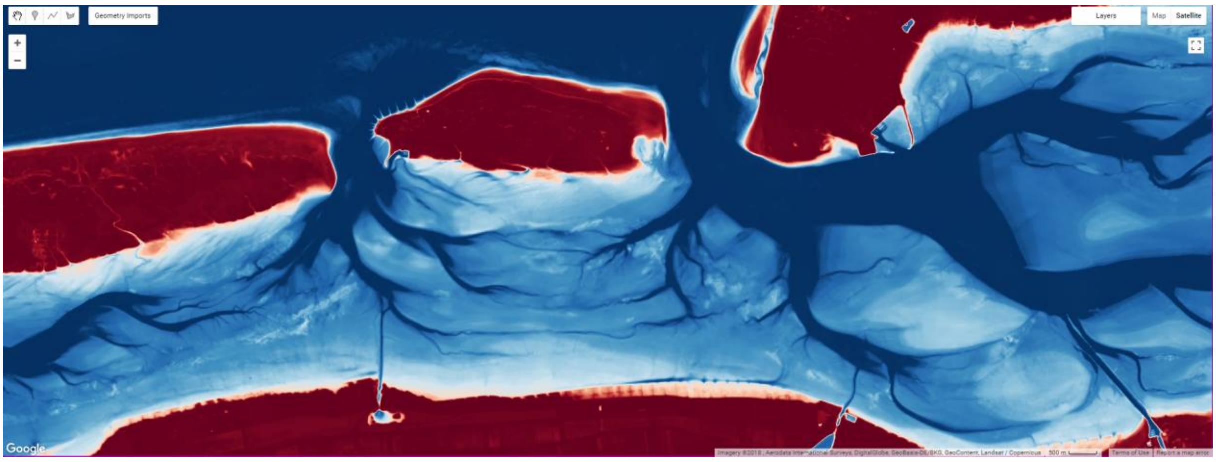


Figure 6 Water occurrence computed as expected value from all NDWI values, using per-pixel cloudiness values as weights (dark blue = permanent water, red = land).

Linking water occurrence to tidal level

In the introduction the coastline was defined as the physical interface between land and water, but this is also the most dynamic part of the coastal zone. Although much of the published literature have studied the problem of coastline position from multispectral images, only a few papers have addressed the problem of mapping the tide coordinated coastline.

Because of the dynamic nature of the ocean waters and of the near coastal lands we introduce the definition of an instantaneous coastline to point out that line position is relative to a given instant of time (Li et al., 2002). Thus, the coastline needs to be defined in a stable vertical datum in order to be used as a reference coastline. If this vertical datum is defined as the linear intersection between the coastal surface and a desired water tidal level, the coastline is called tide-coordinated coastline (Li et al., 2002).

The tidal amplitudes are often amplified near the coast, while at the same time the spatial variability increases because the tidal wave propagation slows down in shallow waters. Tides are small in some regions but can also reach extremes of 13 meters in the Bristol Channel or 12.3 meters in Bay of the Mont Saint Michel, for example. Traditionally, corrections for local sea level have been computed from local tide gauges or tidal forecasts. On a global scale the number of permanent tide gauges is not sufficient to interpolate to arbitrary locations. At the same time, satellite-based altimeter observations of sea level do not have a sufficient temporal and spatial resolution to be used directly for correction of dynamic variations of the sea-level

In this project, the correction for sea level variation is based on use of the Global Tide and Surge Model (GTSMv4.1), which provides instantaneous water level and tide levels with global coverage. To ensure sufficient resolution near the coast, an unstructured grid model is used (Wang et. al. 2022, Irazoqui et. al. 2018 and Kernkamp et. al. 2011).

As the accuracy of the coastline position extracted from satellite images depends on the range of tidal height at the satellite overpass time (Yu et al., 2011), it is important to link to the tidal height at the time of image acquisition. The availability of GTSM tidal information allows retrieving water level at any time and location and compute satellite derived coastline to a coordinated tide level. The availability of the conversion between these vertical reference frames makes it possible to connect data-sets using different vertical reference frames, and conversion to a reference frame of choice for the user. The schematization of the vertical datum referencing process is shown in figure 7.

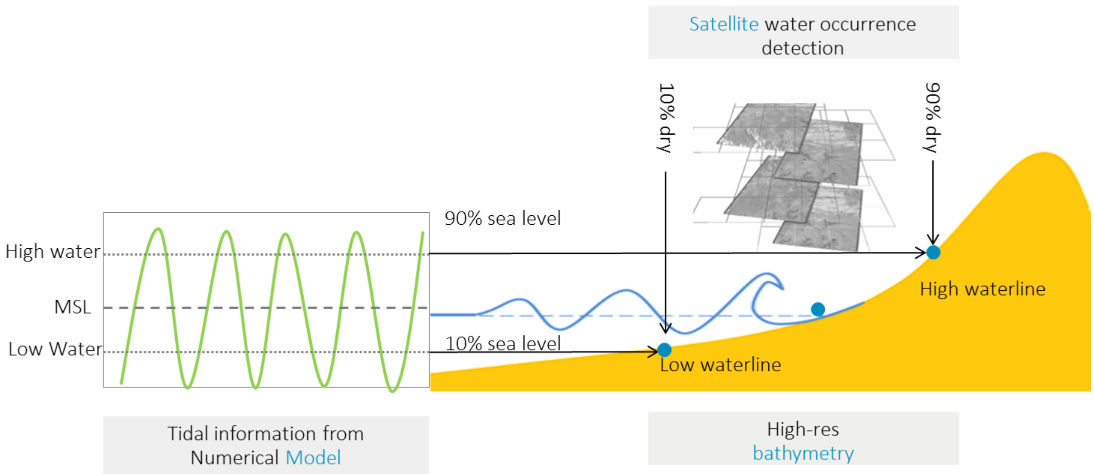


Figure 7 schematization of the vertical datum referencing of satellite derived coastline

Instead of linking to the water level for individual images we used the distribution of water occurrence and the distribution of the local water level to link both. Unfortunately, there was too much noise in the images near the extreme values of the water occurrence distribution, so we had to limit the levels to within the 5% to 95% range. The value of LAT is almost everywhere at a level of more than 95% water occurrence. In the end, it was decided to link LAT to 95%, MSL to 50% and MHW to 95% for the first version of this satellite derived coastline, to describe the maximum tidal range attainable at this time. Future work will aim at more accurate representation of MHW and more extreme levels. The water occurrence grids were contoured on a tile by tile basis.

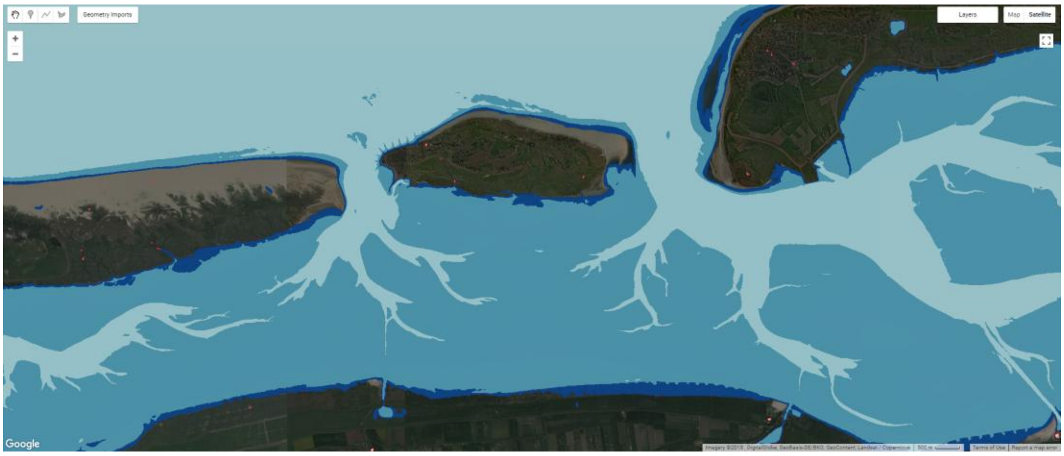


Figure 8 Coastline polygons for MHW, MSL, LAT estimated as 5%, 50%, and 95% percentiles of water occurrence images.

Coastline detection at high latitudes

Deriving coastline for Northern regions such as Greenland and Svalbard can be very challenging due to high cloud cover and the fact that land and water are frequently covered by snow and ice. Furthermore, deriving water/land boundary from optical images in these areas can results in false-positive water detection due to low sun elevation.

However, in recent years there was very little snow and ice end of summer, which makes detection of the coastline easier. In addition, we have used Sentinel 1 radar images to reduce the false positives.

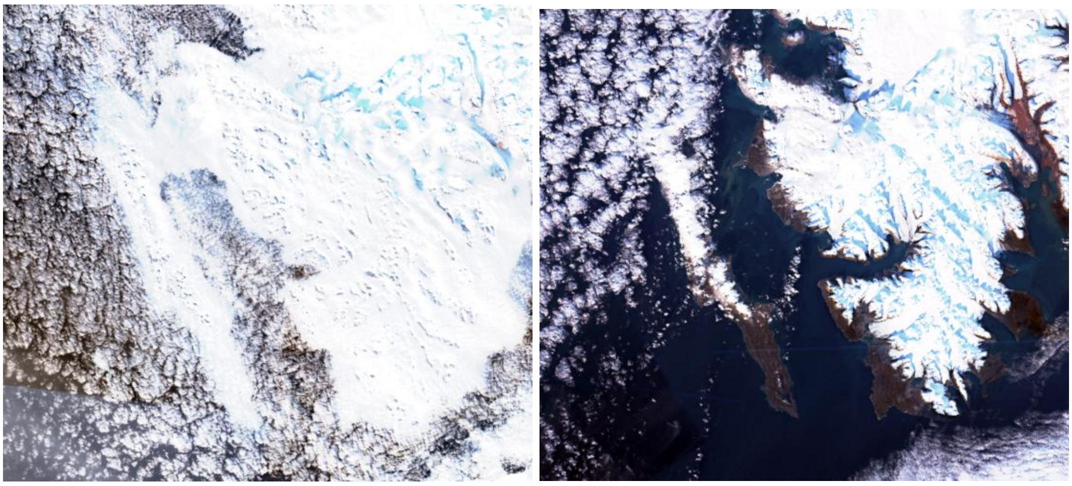


Figure 9 Sentinel 2 optical images of Western Svalbard on March 21 September 25, 2020.

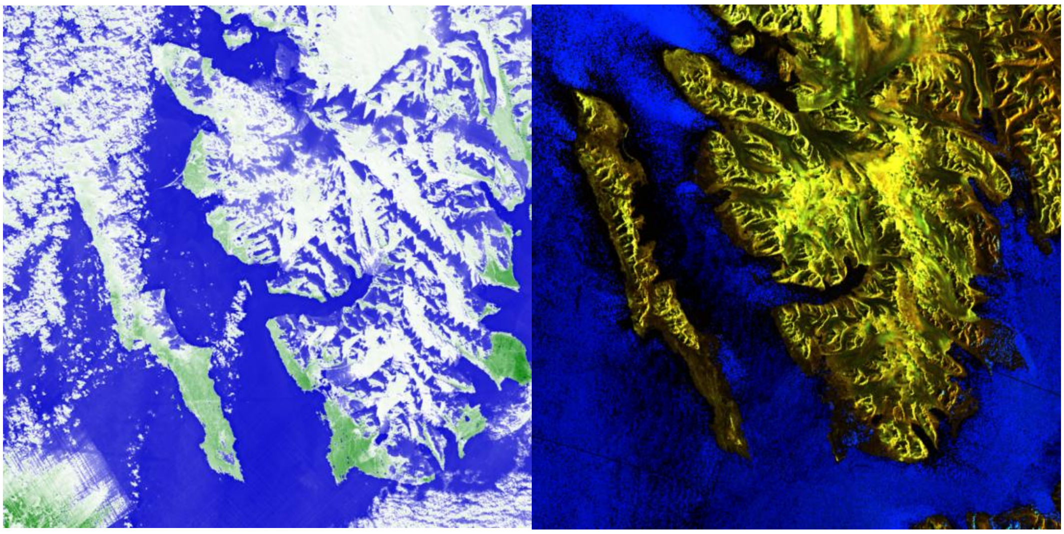


Figure 10 NDWI for Sentinel 2 on September 25 and Sentinel 1 SAR image on September 26, 2020

To overcome these challenges, we have decided to combine optical (Landsat 8) and SAR (Sentinel-1) images acquired only during summer months (June to September). All images acquired during these months are used in processing to generate input features for supervised machine learning algorithm Random Forest (Breiman 2001). The overall algorithm can be outlined in the following steps:

1. For every processing tile, generate input features by combining 100-1000 summer images of Sentinel-1 (HH, HV polarization), use 35% percentile, neighbourhood mean, std as input features
2. For every processing tile, generate input features by combining 100-1000 least-cloudy Landsat 8 images, use 10% percentile, std as input features
3. Generate weak labels using stratified sampling and OpenStreetMap coastline as land use classes, use 1. and 2. as input features
4. Train the first Random Forest classifier with the output = PROBABILITY

5. Remove confusing input samples by analysing probability histogram
6. Train the second Random Forest classifier with the output = CLASS
7. Generate the final coastline

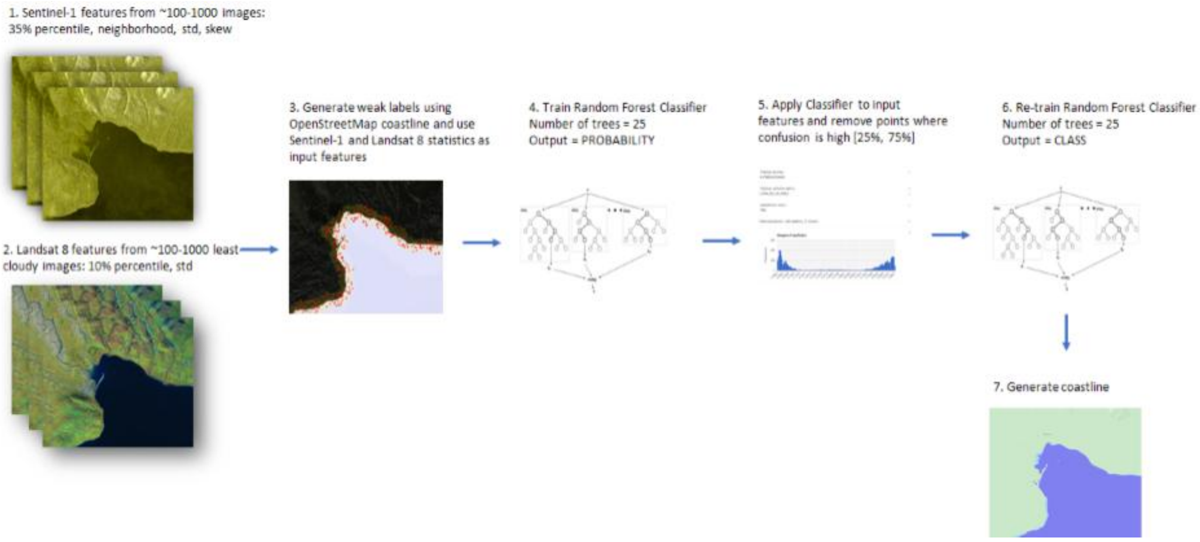


Figure 11 Workflow of the semi-supervised algorithm used to generate the coastline for Greenland, Jan Mayen and Svalbard from Sentinel-1 SAR and Landsat 8 optical data

The resulting coastline shows a very high performance, but still required minimal manual checks to eliminate false land detecting in the areas where number of satellite images is low or where confusion is very high (e.g. water areas always covered by moving ice or very steep hilly areas).

Next the coastline was generated from the raster classification to vector format at 10m resolution. Several additional steps were applied to ensure quality of the results, such as:

- Overriding pixel classes as deep water (EMODnet < -50m), as shown in Figure 12
- Overriding pixel classes as land for high elevation pixels (ALOS DEM > 50m)
- Manual overriding of pixels to be water or land based on visual inspection
- Fallback to OpenStreetMap coastline for the most Northern regions, Figure 13

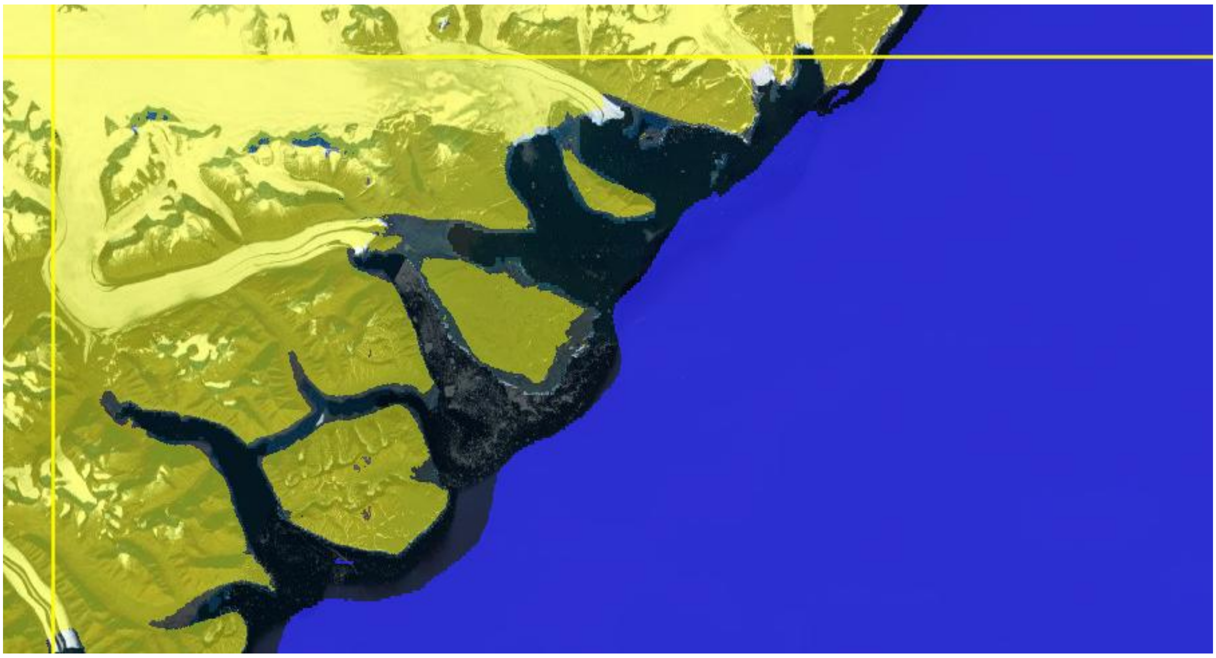


Figure 12 The classified coastline was combined with EMODnet to remove some of off-shore false-positives created by floating ice, all pixels where water depth is < -50m were classified as water. Correspondingly, all pixels where the ALOS DEM was higher than 50m were classified as land.

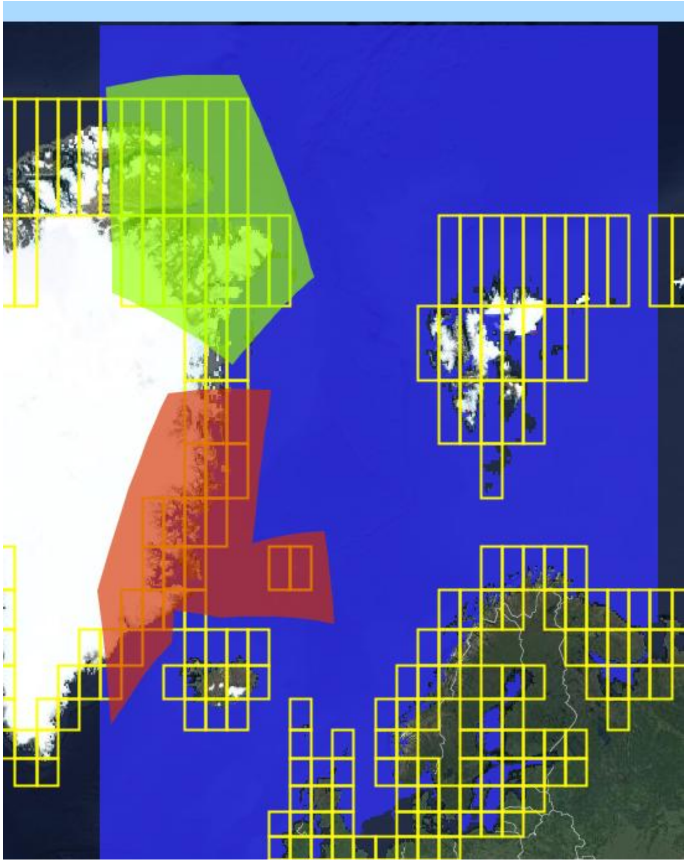


Figure 13 Greenland tiles where OpenStreetMap was used to extract coastline (green) and where Random Forest based algorithm was applied (red)

It's important to note that the Northern regions marked green in Figure 13 are much smaller than they seem, because the area is stretched by the Web Mercator projection used for visualization.

The fallback to the OpenStreetMap coastline was applied only to the tiles where ice was present on almost all optical or SAR images, like shown in Figure 14, where some of the areas are misclassified as land due to permanent ice present in all images. Further improvements may be possible in future versions of the classification scheme, but at the moment too many false islands are generated.

Figure 14 Comparison of Google base map (left), Landsat 8 5% TOA reflectance composite (middle), and reconstructed coastline (right). Some areas with almost always permanent ice present on the sea surface are still classified as land.

For the Arctic regions, we did not derive separate low and high-water coastline, since limiting the images to summer only in combination with the poor lighting and high cloud cover leaves too few images for this type of analysis. Fortunately, much of the coastline in this region shows only a small inter-tidal zone. This implies that in the final coastlines the data for low-, mean- and high-tide will coincide.

Coastline detection in the Caribbean

In the 2022 release of the EMODnet satellite derived coastline we have added the Caribbean. In large parts of the Caribbean the water is clear and land-water detection works well, so we have used the same methods as for European continental waters. However, in some parts in the southern Caribbean something like water vegetation or silt is mistaken for land sometimes. There are other exception, such as the salt works in Bonaire. These basins contain a thin layer of seawater that is evaporated to produce salt. The algorithm correctly classifies these pixels as water, but it's not part of the sea of course. However, due to the proximity of the sea the coastline estimates are affected here.

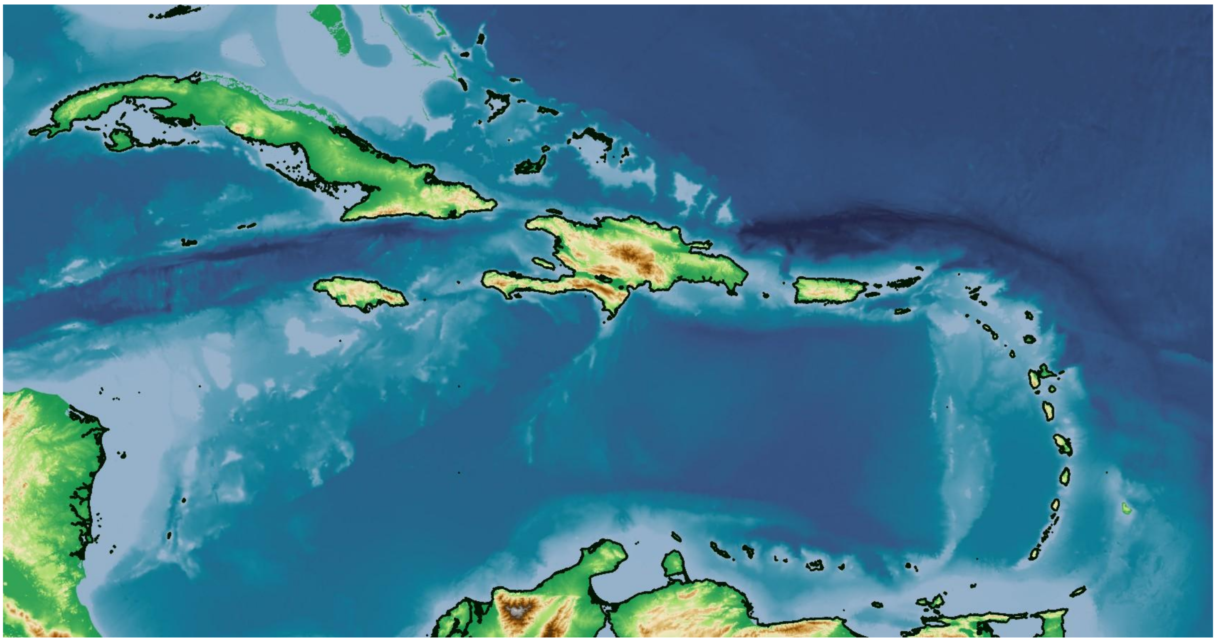


Figure 15 Overview of Caribbean are with coastlines in black.

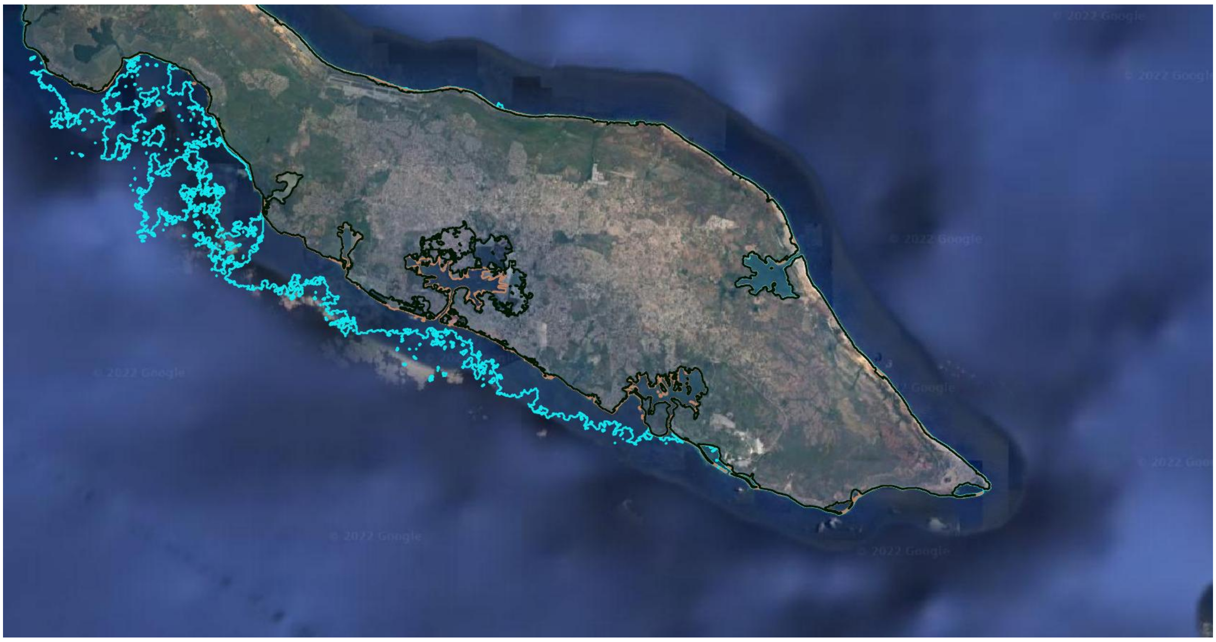


Figure 16 Example where the low-water coastline is not detected well (southern Curacao)

Figure 17 Salt works in Bonaire

Post-processing and generation of final products

After land-water detection and contouring, as described above, there are still several steps needed to produce a final set of products. First, we remove water that was detected, but where we do not consider it to be part of the coastline. Then we compute the inter-tidal area as the area between the low water and high-water. Finally, we need to merge the data, since this is computed and exported in GEE, in many rectangular tiles.

Export of polygons per tile

After processing optical satellite data to the level of polygons that together cover the water as detected, we exported the data. Since the GEE computations were organized in small rectangular areas to facilitate parallel computation, this resulted in many files. The figure below gives an overview of the division into tiles. Each tile has an ID, i.e. the number also shown in the figure below. For efficiency, the tiles that consist entirely of land or entirely of water were excluded from the computations in GEE. After the export, we added these back into the dataset.

All gaps in the data that existed in the previous version of the coastline have now been filled. The coastline should cover the entire region shown below.

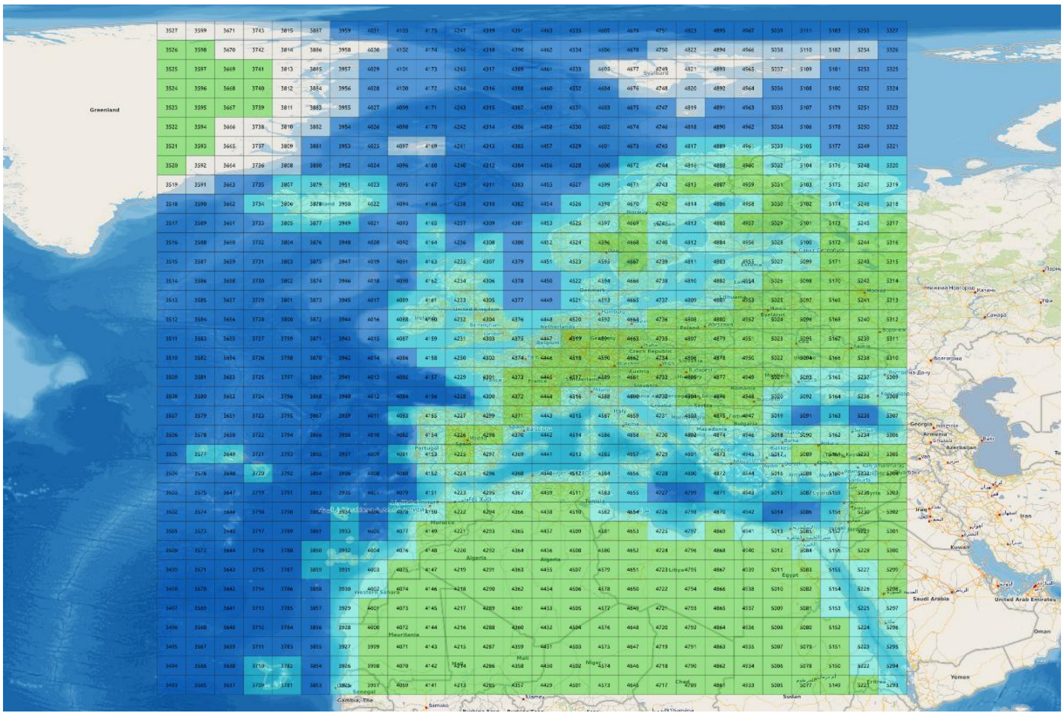


Figure 18 Tiles exported and their status: land only (green), water only (dark blue), part land/part water (light blue), combined optical-sar detection (white)

Filtering lakes

The water detection algorithm does not distinguish between fresh and salt water, nor between coastal versus inland water, resulting in many lakes and other surface water to appear that are not considered to be part of the coastline. It may not be possible to create a clear separation in all cases. The aim of the processing step described here is to eliminate smaller waters that are not connected to open sea. This eliminates many features. We have designed the filtering procedure and threshold to be conservative, i.e. not to delete waters that might be part of the coastline. This implies that the dataset will contain water-land boundaries that we would not consider to be part of the coastline.

The figure below shows part of the Netherlands before and after filtering of small disconnected waters. It can be seen that the North Sea Channel connecting the harbour of Amsterdam to the North Sea is connected to the North Sea in this data-set, but in reality there are sluices near the coast, that separate the water in this channel from the North Sea. Apparently, the sluice gates were not detected from the satellite images. In the current version of the satellite derived coastline we have kept these features. In future versions, we may remove the most important internal waters manually.

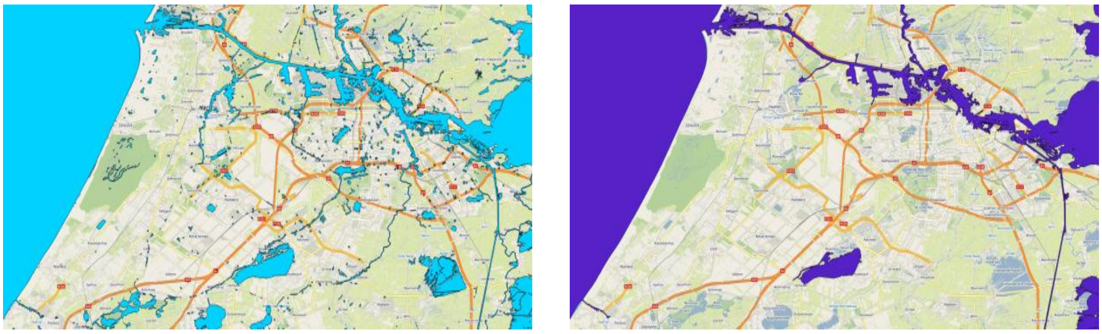


Figure 19 Example of images before (left) and after (right) after filtering water bodies that do not belong to the coastline

Computation of inter-tidal areas

To compute the inter-tidal area, we have computed the set-difference of the area covered at high-water minus the area covered at low water. The figure below gives an example for a part of the Wadden Sea (Netherlands). In the final dataset the parts for each of the tiles were merged into one dataset.

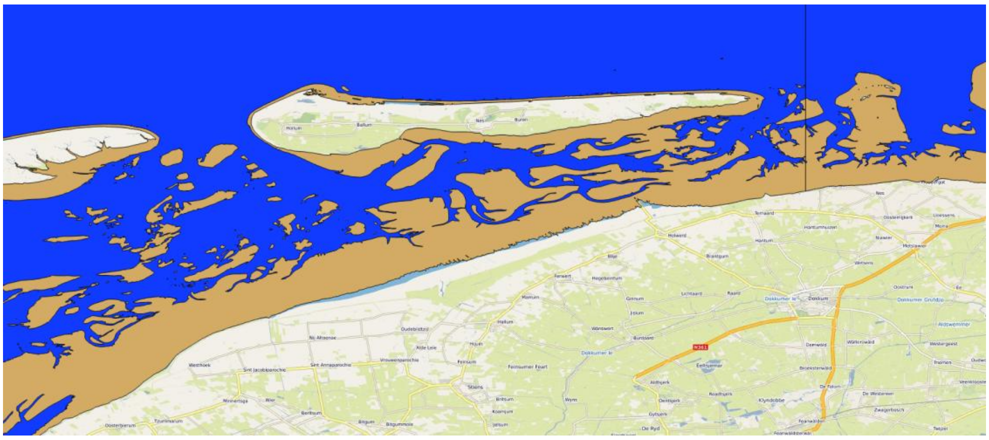


Figure 20 Inter-tidal area (Orange color), computed as set-difference of water at high-water and at low-water

Dataset for European continent

Finally, the parts of the coastline per tile were converted from filled-polygons to poly-lines. Figure 21 illustrate the SDC plotted as a line.

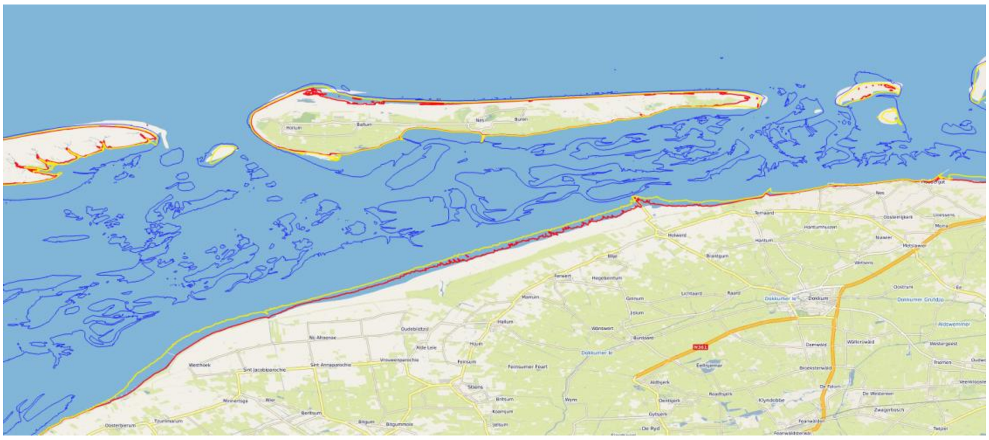


Figure 21 Plotted coastline as poly-line format (Final product delivered)

Dataset for Caribbean

The satellite derived coastlines for the Caribbean were collected into a separate dataset. The formats and processing were kept identical.

Coastline comparison

European continent

This section presents a visual comparison between the Satellite Derived Coastline (SDC), the coastline derived from Open Street Maps[2] (OSM) and the coastline provided by EMODnet project partners.

The OSM coastline has been derived from Open Street Map ways tagged with `natural=coastline`. This data contains all the detail available in OSM. For small scale maps (small zoom levels) it might be too detailed and therefore slow to use and not well readable. The OSM coastline projection is in WGS84 (EPSG:4326) or web Mercator (EPSG:3857). The coastlines can be obtained as lines and/or land polygons and/or water polygons.

Within the EMODnet Bathymetry project, one task was to gather official coastlines for the European waters. Information about coastline has been gathered per country, the data comes in different coordinate system and at different spatial resolutions. This data set is also used for the visual comparison and we will refer to it as "Official Coastline".

The visual examination after the retrieval process showed that the SDC coastline is generally in good visual agreement with OSM and the official coastline. The comparison suggests that the discrepancy between the SDC and the other data sets remains within the pixel size in sandy beaches. This comparison therefore bodes well

[2] Coastline in OSM is defined as the mean high water spring line between the sea and land (with the water on the right side of the way). https://wiki.openstreetmap.org/wiki/Map_Features

for future attempts to detect coastline changes of larger magnitude than the pixel resolution (10 m).

There are areas where there is a bigger discrepancy between the SDC, OSM and the official coastline. For example, in areas under land reclamation or human intervention the coastline changes rapidly over time. Resolution and accuracy of OSM coastline is variable since it is the result of many contributions by many people and from many sources.in the other hand updates in the official coastline might not be as fast as the changes due to human interventions. To illustrate this example we present Figure 22. The figure shows Luka Ploce in Croatia, where SDC gives a more detailed contour of the Port in that area.

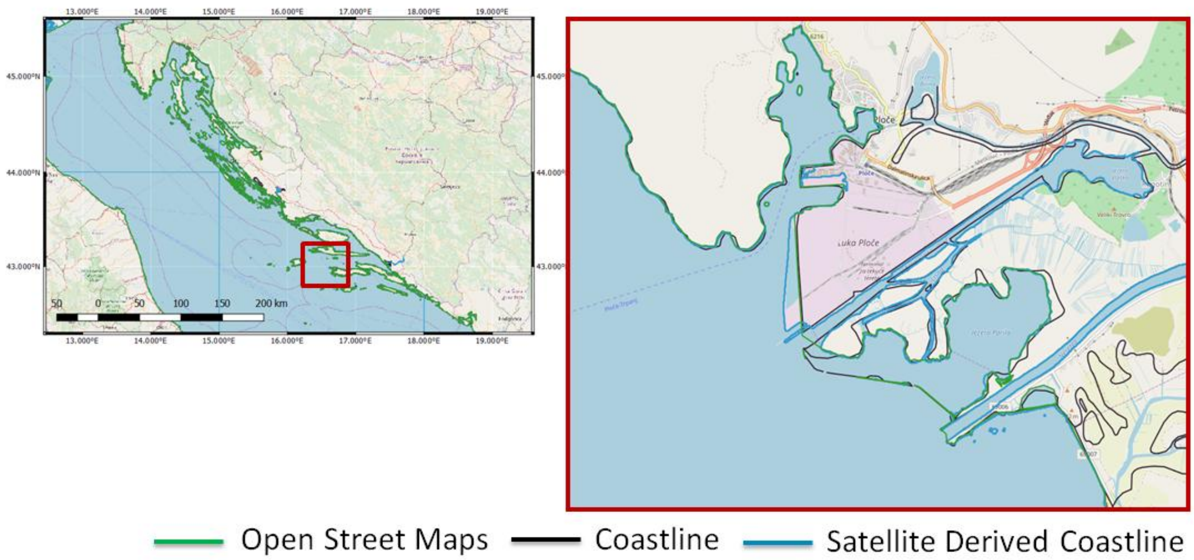


Figure 22 Croatia (Luka Ploce): comparison between SDC (high water), OSM and coastline from official sources

The fact that the biggest discrepancy while comparing the coastlines were consistently observed at intertidal areas, indicates that the current tide level, possible effects of storm surges and the beach slope, play and important role. Figure 23 present the comparison between the different coastlines in an intertidal area. The chosen case is situated in the Netherlands. Terschelling is one of the islands situated in the Wadden Sea. This area is the largest unbroken system of intertidal sand and mud flats in the world. Morph dynamics is very active here, so coastline changes rapidly. The beach is also very flat, so that small differences in approach lead to large spatial differences. The difference between the SDC, the OSM coastline and the official coastline can reach a difference up to 650 meters.

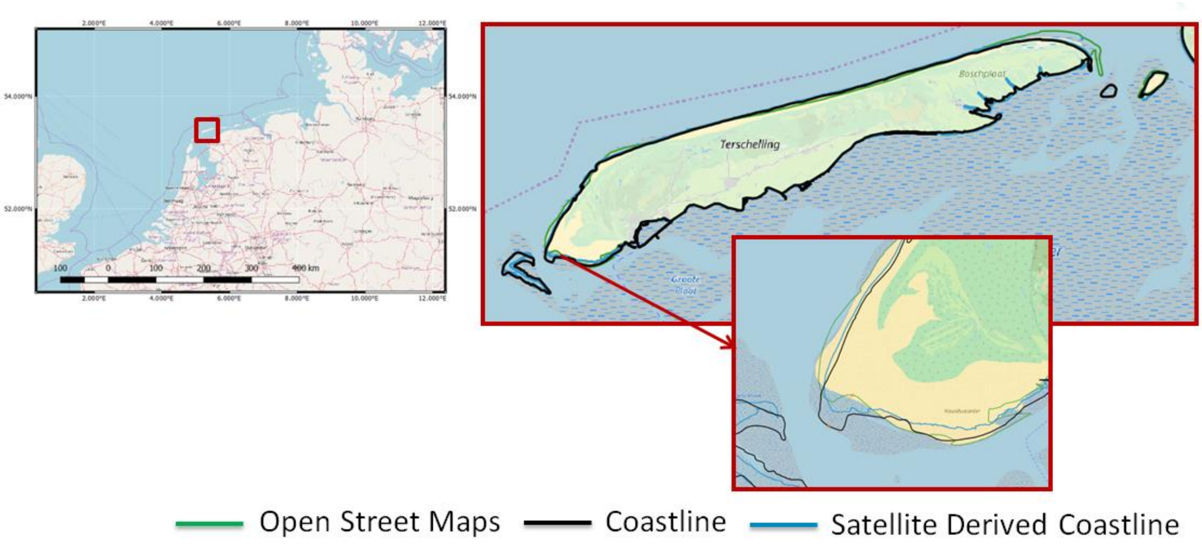


Figure 23 Netherlands (Terschelling): comparison between SDC (high water), OSM and coastline from offical sources

Coastline has been defined as a line that forms the boundary between the land and the ocean. Nevertheless, there are some regions that line cannot clearly be established. Precisely in those regions, the discrepancy between the SDC, the OSM coastline and the official coastline tend to increase. Figure 24 present a peculiar case in Portugal (Aveiro) where SDC provide more detailed information that OSM and the official coastline.

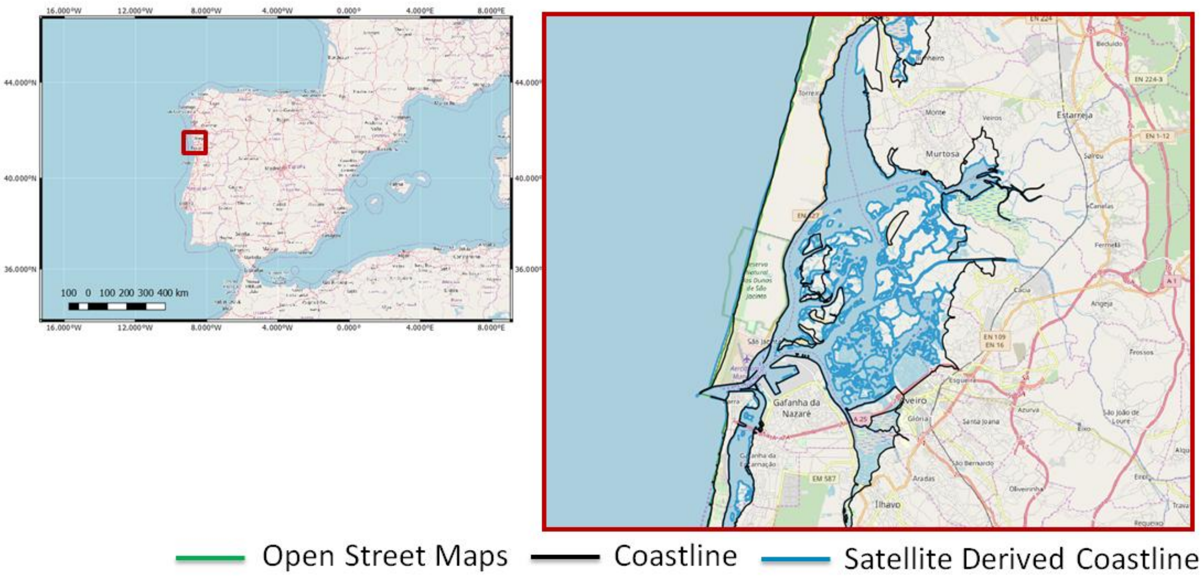


Figure 24 Portugal (Aveiro): comparison between SDC (high water), OSM and coastline from offical sources

At high latitudes the performance of the new detection algorithm is generally good. Difficulties arise in some areas which combine frequent ice and high cloud cover rate. Note also that the edge of glaciers is dynamic and thus depends of the timing of the satellite images used. Meltwater from glaciers also introduces much sediment into the water, which makes detection harder.

The figures below compare the new method (green) against Open StreetMap (OSM red), with a Google satellite image as background.

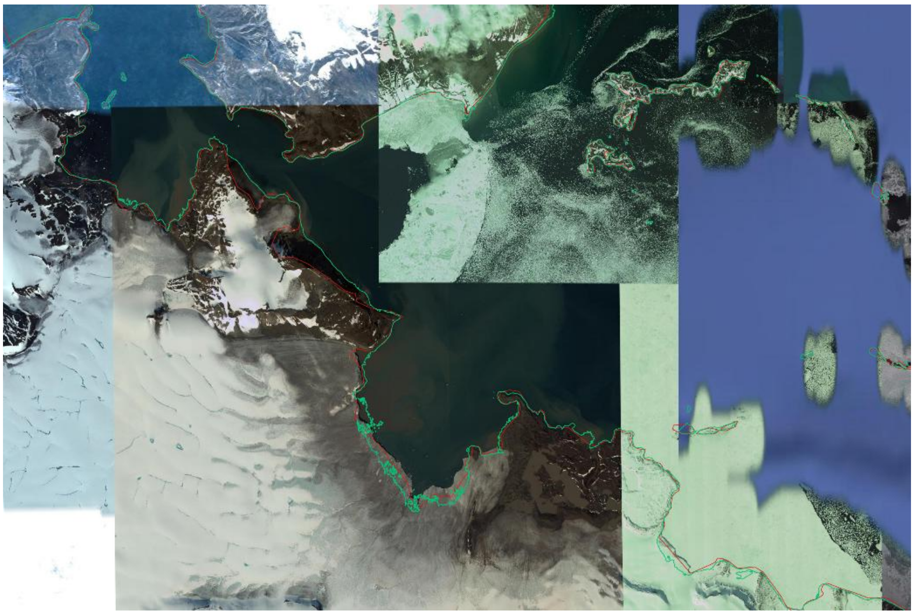


Figure 25 SDC (green) against OSM (red) for eastern Svalbard

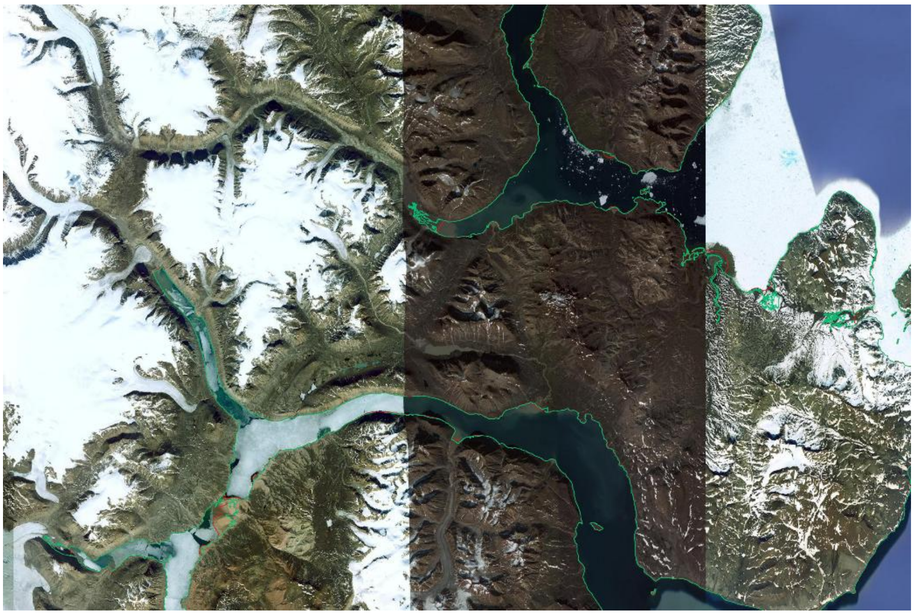


Figure 26 SDC (green) against OSM (red) for eastern Greenland

Comparison Caribbean

Here we briefly compare the satellite derived coastlines for the Caribbean to the OSM coastline for some selected cases for illustration. Figure 27 shows the estimated coastlines in comparison to OSM (red). In most parts the OSM coastline is a bit further inland. This could be close to a very visible high-water line that is only reached very infrequently.

Figure 27 Sample coastlines at Antigua (Open Streetmap in red)

Figure 28, below shows an example where a shadow from a cliff confused the land-water detection. OSM is also quite inaccurate here.

Figure 28 Dominica with a cliff on northern side

Figure 29 shows an example where a small mangrove was classified as and by the satellite derived coastline.

Conclusions and recommendations

In this report we described the methods used to derive a coastline from optical satellite imagery. In comparison to other sources, the coastline retrieved from satellite images shows good agreement in most areas. It is consistent with the Open Street Map (OSM) and the official coastlines, giving confidence that the interpretation of different positions of SDC shows a real representation of the coastline at different datum.

For the 2020 release, a new detection algorithm has been developed and applied for hight latitudes, where snow and ice, high cloud cover and low sun angle make detection difficult. The method is based on a combination of optical images and Sentinel-1 SAR images. The detection works well, except in the most northern part of Greenland.

Although the quality is generally high, the following aspects could be improved:

- At high latitudes, there are a few areas with too few useful images, resulting in some ice to be classified as small islands. Even with the current quality checks not all were removed. Improvement is desirable in future versions

- We did not succeed so far to detect the coastline at low water for Iceland and the Faroe Islands. Perhaps the very high cloud cover and poor lighting conditions are to blame. This needs further investigation.
- NDWI is not robust for very turbid water. In the future, we wish to extend the analysis to use MNDWI and maybe other indices to improve quality for these regions (in particular, UK) is needed.
- Shadows at steep coasts and spray in the surf zone is sometimes accidentally classified as land.
- A further exploration and improving of the algorithm in urban areas is needed. For example, construction activities during the period of the analysis may lead to misclassification of these areas as inter-tidal.

For the 2022 release, the area was extended to include the Caribbean. Although this works well in general, there a several aspects that can be improved

- The low-water coastline seems quite noisy in several locations. Perhaps the detection thresholds need to be adjusted here.
- The land-water detection algorithm is confused by several coastal features, such as cliffs, wave breaker zones and vegetation

In addition the connection to the land-sea mask for the bathymetry could be made more consistent and the accuracy of the connection to the tidal levels could be improved.

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Annex – digital satellite derived coastlines and intertidal areas

The satellite derived coastlines and dataset that delineates the inter-tidal areas of Europe as determined and described in this report are available for viewing and for downloading as digital files in shape format. Therefore, these coastlines and inter-tidal areas have been added as an extra Bathymetry layer in the EMODnet central map viewer service (https://emodnet.ec.europa.eu/geoviewer/) which allows users to view these and also to download as digital files in shape format. The layers have also been included in the OGC WMS – WFS services[3].

The coastlines data set has also been added to the central Products Catalogue as one of the EMODnet Bathymetry products. Check:

https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/search

The coastlines are given for the three most used levels, i.e. Lowest Astronomical Tide (LAT), Mean Sea Level (MSL) and Mean High Water (MHW). The inter-tidal area is derived as the area between the coastlines at MHW and LAT. The extra layer is also included in the WMS-WFS service.

[3] See https://tiles.emodnet-bathymetry.eu for an overview of the EMODnet Bathymetry OGC services