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RECONSTRUCTION OF SEA LEVEL CHANGES IN NORTHERN FRANCE FOR THE PAST 300 YEARS AND THEIR RELATIONSHIP WITH THE EVOLUTION OF THE COASTAL ZONE

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Study area

VARIOUS COASTAL MORPHOLOGIES

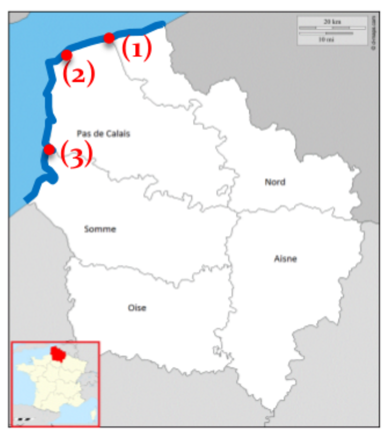


Fig. 1. : Location map of the study area showing the various coastal morphology

http://www.amis-hom-arts.com/article-la-baie-d-authie-vue-du-ciel-par-l-ami-guy-118184130.html

The Hauts-de-France coastal zone (Northern France, *Fig. 1*), is morphologically diversified, leading to a complex dynamic in the area. We can classify this coastline such as:

- **Sand beaches (1)** with aeolian dunes and intertidal beach of various size and morphology.
- **Rocky coast** with cliffs between Boulogne-sur-Mer and Cap Blanc Nez **(2)** (elevation range between 5m to 133m).
- **Estuarine** and **empoldered tidal flats (3)** : in the South with the Authie, Canche and Somme estuaries; strong variations in the coastal hydrodynamics and sediment dynamics

TIDAL CHARACTERISTICS

Coefficient	Berck-sur-Mer	Boulogne-sur-Mer	Wissant	Calais	Dunkirk (Dunkerque)
45	5.05	4.6	4.15	4	3.5
95	8.5	7.75	6.95	6.5	5.45

Table 1. : Tidal range in the study area (Data from [15])

The tidal regime is **semi-diurnal** and **macrotidal**, with large tidal ranges that diminishing from the Somme estuary to Belgium (*Table 1 & Fig. 2*). Due to large tidal amplitude, tidal currents are strong, they can reach maximum nearsurface speeds of 1.5m.s^{-1} during flood tide and 1.35 m.s^{-1} during ebb [2]. Measurements in this sector show an asymmetryic tidal current resulting in a **flood dominated current**, responsible for a **net regional sediment transport** to the North in the English Channel and to the North-East in the North Sea [2].

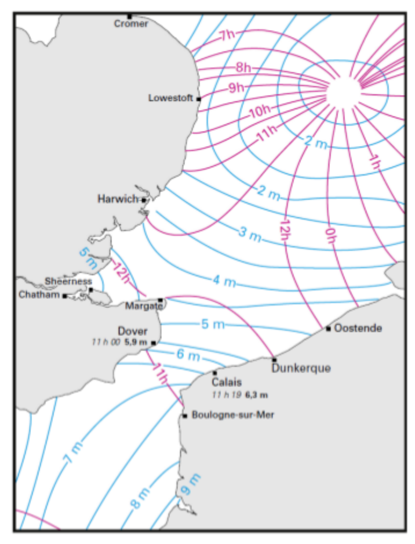


Fig. 2. : Cotidal chart fort the East of the English Channel and the South of the North Sea. Blue co-range lines run between points of equivalent tidal ranges (spring tide here), while red co-time lins run between points where high waters are reached at the same time. [10]

NEARSHORE SANDBANKS

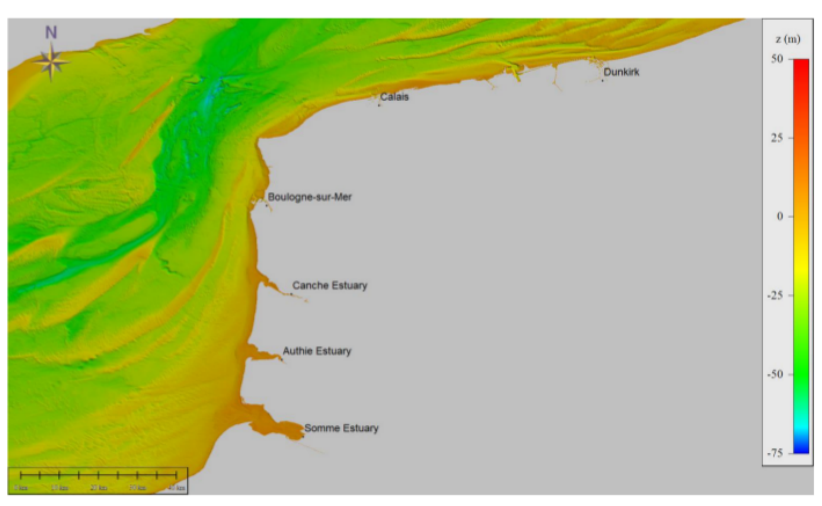


Fig. 3. : Location map of the study area showing the position of nearshore sand banks (2015 Bathymetric data from Shom)

Sand banks are particularly **widespread** in the eastern English Channel and the Southern North Sea forming linear **shore-parallel** or **slightly oblique** sand bodies about 10-30km long and 1-3km wide (*Fig. 3*). In the Southern North Sea nearshore sand banks actively migrate onshore and/or longshore [1].

Migration of nearshore sand banks can have very different **effects** on **coastal hydrodynamics** and **sediment dynamics**, depending on the depth, orientation and distance from the bank to the coast [9].

Aims of the study

COASTLINE EVOLUTION

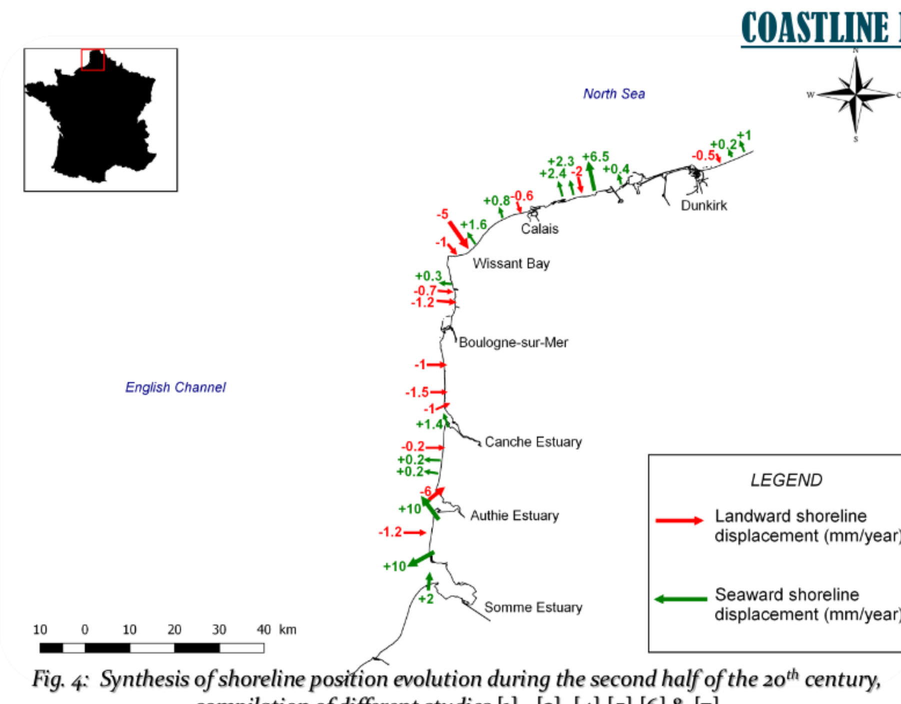


Fig. 4: Synthesis of shoreline position evolution during the second half of the 20th century, compilation of different studies [1] , [3] ,[4] [5] [6] & [7]

The analysis of shoreline position during the second half of the 20th century (*Fig. 4*) revealed a **high spatial variability** in **coastline evolution** [1],[6].

Anthropogenic factors, such as implantation of **major harbor** (e.g. Calais and Dunkirk); **nuclear power station** in Gravelines; and implementation of many **infrastructures** to stabilize the shoreline (e.g groynes); lead to a big **reduction in natural coastal areas**.

Inlet sides and channels **migrate very rapidly northward in the estuarine sector,** due to the progression of the southern flank and a widespread erosion of the northern shore for the Authie and the Canche inlet.

In the Somme estuary, the shoreline evolution of the north flank of the inlet was previously characterized, from 1775 to 1950, by an intensive erosion (-4 to -7 m.year^{-1}) [7]. Then, a **reverse trend was observed since 1950** with a seaward shoreline displacement of the north side. (*Fig.4*).

Where & Why shoreline evolution' trends change ?

The first aim of this study is to use bathymetric and shoreline data available since 1800 to answer this question and have a better understanding of the evolution of the coastal zone on a larger time scale.

SEA LEVEL VARIATION

Accurate information on sea level variations, especially in coastal areas, is crucial for tide measurement, navigation (allow safe access to harbors) and studies of coastal environment [10].

Globally, **tide gauge** estimates the average rate of sea level change over the last 50 years as **+1,8 ±0,3 mm.year^{-1}** [11], while **altimeter measurements** revealed a sea level rise of **+3,29 ±0,5 mm.year^{-1}** since January 1993 [14]

Despite this general accelerating and rising trend in the mean sea level, there are **marked regional differences** that vary between -10 and 10 mm/year (*Fig. 5*).

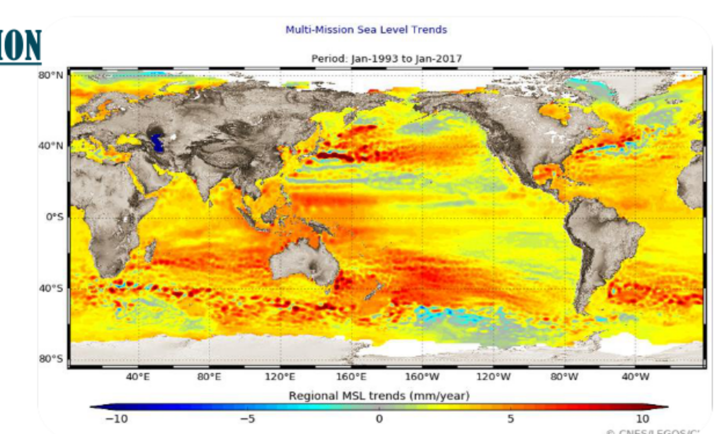


Fig. 5 : Combined map of regional patterns of observed sea level (in mm/year). Credits EU Copernicus Marine Service, CLS, Cnes, Legos) [14]

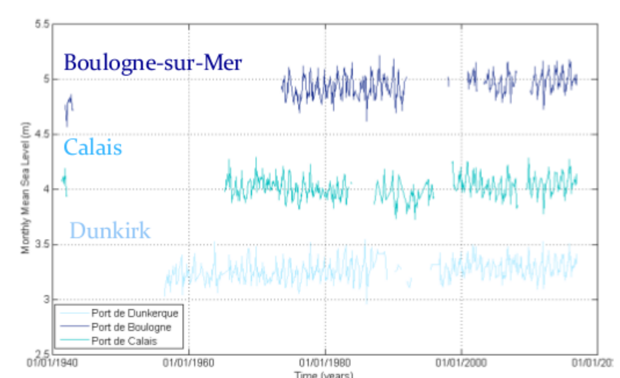


Fig. 6 : Monthly Mean Sea Level for Dunkirk, Calais and Boulogne-sur-Mer since 1940 [16]

In the North Sea and the English Channel, for example, variability may occur between close locations [13]. For Dunkirk, Calais and Boulogne-sur-Mer (*Fig. 6*), **less than 50 years of sea level records online** [14] were available with many gaps. This dataset is not long enough to calculate a statistically significant sea level trend. Nevertheless, data archaeology activities will help fill in the gaps in the dataset and reconstruct sea level change through the years.

Ability to reconstruct sea level change using data archaeology activity ?

The second aim of this thesis is **to search for and add analogue tide gauge charts and sea level ledgers to sea level series of these 3 harbors** to remove inter-annual and decadal sea level variability.

Evolution of the coastal zone since the 19th century

HISTORICAL SURVEYS

Fig. 9 a. : Bathymetric map for Dunkirk in 1879

The morphological evolution of sand banks and adjoining seafloor in Northern France is studied using hydrographic field sheets from the Shom, spanning from the early 19th century to the beginning of the 21st century (*Fig. 9a.*).
Oldest bathymetric surveys were done thanks to a **sounding line** (or lead line) which is a length of thin rope with a plumb bob at its ends. In the beginning of 1900, **echo sounding** method was used and allowed a greater amount of data.

The first step was to identify common periods between all surveys around the study area (*Table 2*). Selected maps were then scanned in a relevant resolution and digitized with ScanBathy software (© Shom).

Selected date
1835-1836
1878-1879
1911
1933-1934

Table 2 : Selected periods

SCANBATHY

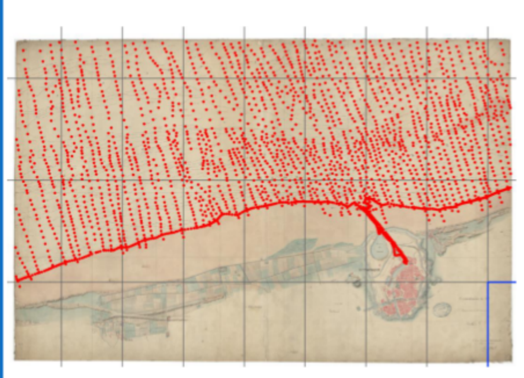


Fig. 9 b. : Digitization with ScanBathy

Map treatments include several procedures:

1. **"ScanAdjust"** is a **georeferencing** efficient tool, using cartographic annotation (e.g.crosses or grids) to compute geometric models.
2. **"Soundings digitizing"** allows to segment the map into boxes (grey lines in *Fig. 9b.*). In each box, **sounding position and depth were manually entered** by the operator (semi-automatic and full automatic mode being available but not appropriate for old maps).
3. **"Production control" check** and potentially edit the values of the soundings. A validation grid is generated after checking that each cell included a sounding inside.
4. **"Export"** : after checking, bathymetric data can be downloading as a **XYZ file**.

DIGITAL TERRAIN MODEL (DTM)

A critical point is to **convert data into present-day cartographic system**.

- **Positioning**: old maps were georeferenced in local geodetic systems and converted to the system WGS84.
- **Distance: feet & inches were** converted to **meter** ; **toise** to **meter**.

Then, when survey area was consistent, interpolation was made and processed data were used to create contour **DTM** using both GMT (Generic Mapping Tools) and Global Mapper. DTMs are obtained by linear interpolation using a **Delaunay triangulation** (*Fig. 9c.).*
In addition comparison between different periods and a recent DTM (*Fig. 9d.)* allow us to calculate changes in sediment volume across the nearshore zone.

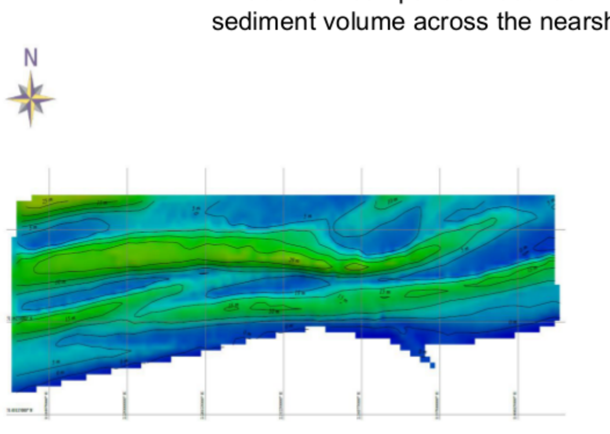
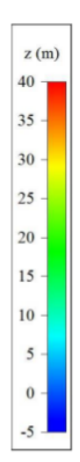


Fig. 9 c. : DTM obtain for Dunkirk, 1879



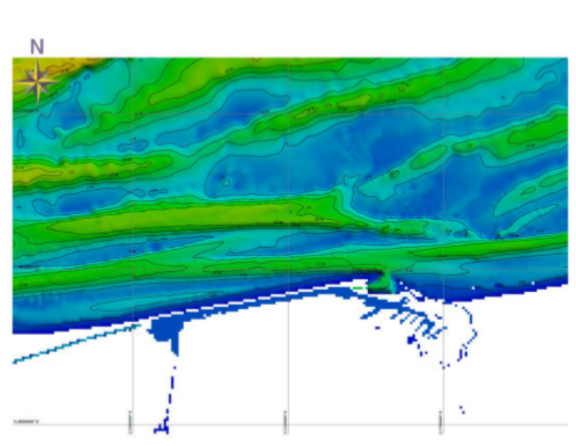


Fig. 9 d. : DTM for Dunkirk, 2015 (Shom, HOMONIM)

Reconstruction of the Sea level time series

INVENTORY

The first primordial step was the **inventory of existing sea level observations** scattered in various institutions in France (*Fig. 7*).

- **1700**: very first identified measurements, more than a year, corresponding to visual observations at a tide staff located in Dunkirk.
- Since **1850**: **regular measurements** using mechanical float tide gauges. These devices have changed and evolved over time allowing measurements up to 1996 for Dunkirk, 1998 for Calais and 2000 for Boulogne-Sur-Mer.
- Later, these 3 ports have been part of the **French RONIM** network operated by **Shom**, and the old mechanical tide gauges has been replaced by a **radar tide gauge**.

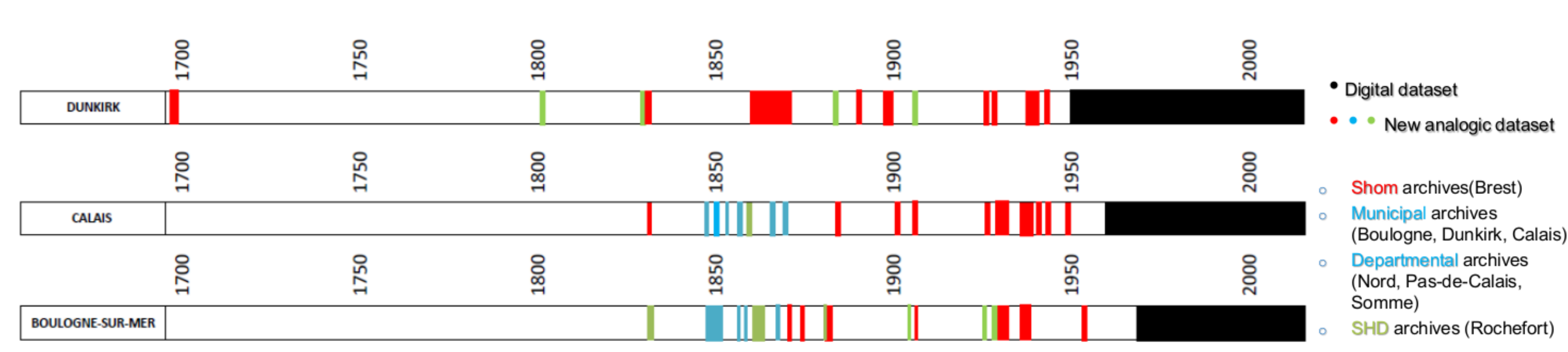


Fig. 7. : Inventory of existing sea level observations for Dunkirk, Calais and Boulogne-sur-Mer

DIGITIZATION

In order to make the historical datasets available for studying the sea level evolution, the existing ledgers and tidal charts have to be digitized(*Fig. 8*).

- **Handwritten ledgers** have to be **manually digitized**. During this work, verification procedures have to be set up to identify errors related to transcription and/or mistakes made by observers.
- **Tidal charts** are **semi-automatically digitized** by using the NUNIEAU software [12]. NUNIEAU is a signal processing tool based on color recognition.

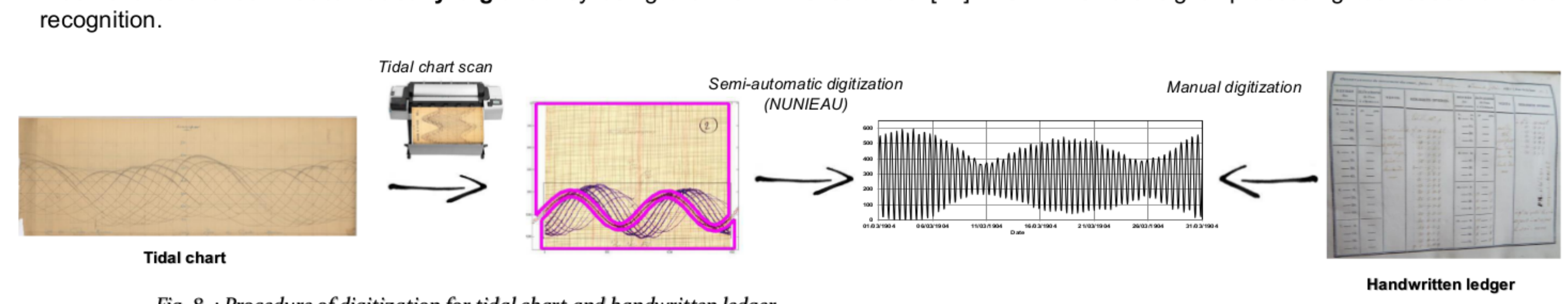


Fig. 8. : Procedure of digitization for tidal chart and handwritten ledger

QUALITY CONTROL PROCEDURE

A quality control procedure is a crucial in order to make these **data consistent** over time in terms of **time systems and vertical reference**, which both evolved during the studied period.

- Time systems : oldest datasets were generated with Apparent Solar Time (**AST**) then Mean Solar Time (**MST**), and finally with Universal Time (**UT**). All the data are **converted thus into the UT system** by applying the "equation of time" and a correction based on the longitude difference between the current location and Greenwich.
- **Vertical reference level:** reducing the reconstructed time series to a **common vertical reference level** implies to precisely know the different levels used as tide gauge zero and/or chart datum over the time and thus to compare lots of diverse and scattered documents (metadata linked to measurements, leveling reports, observers' notes, letters, …).

Perspectives

Sea level reconstruction :

- What analyses will be useful for **annual** and **monthly MSL** for each data set?
- Tool for identification of **extreme sea level** since the beginning of records.
- **Comparison** between **long sea level records** with English stations (Newlyn, Liverpool, Sheerness), French stations (Brest, St-Nazaire), Belgians stations (Ostende, Nieuport) or Netherland stations (Hoek Van Holland, Vlissingen).

Coastal zone evolution :

- Follow the **bathymetric evolution** on the **complete area** ? Or focus on very **particular sector** ?
- Relevance of **spectral wave model** for simulating wave propagation over the present day and previous bathymetries in order to evaluate the **effects of changing seabed morphology on wave refraction.**

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