Historical sea level data rescue to assess long-term sea level evolution: Saint-Nazaire observatory (Loire estuary, France) since 1821

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Introduction

Nowadays, the study **of the global sea level rise is a strong societal concern**. The analysis of **historical records of water level** proves to be an ideal way to provide **relevant arguments regarding the observed trends**. In France, many systematic sea level observations have taken place since the mid-1800s. Despite this rich history, long **sea level data sets digitally available are still scarce** (Pouvreau, 2008). Currently, only the time series of Brest (Wöppelmann *et al.*, 2006), Marseille and recently the composite one of the Pertuis d'Antioche (Gouriou *et al.*, 2013) span periods longer than a century and are available to be taken into account in studies dealing with long term sea-level evolution. In this context, an important **work of "data archaeology**" is undertaken **to rescue the numerous existing analog historical data that is part of the French scientific and cultural heritage.**

The present study focuses on **the measurements carried out at the sea level observatory of Saint-Nazaire.**

Aims

- **Rescue historical sea level data.**
- **Improve our knowledge on trends in sea level components on the Atlantic coast on large scale and on the coast vulnerability at more local scale.**
- **Study the influence of the Loire river and of large-scale engineering works on water level measurements.**

Study area

Saint-Nazaire is located on the French Atlantic coast in the **mouth area** of the **macrotidal Loire estuary**. Since the mid-19th century, with the increase of maritime traffic and the harbor development, the city has reclaimed from the sea, and the tide observatory equipped with a tide gauge has been created (***Figure 1***).

This particular location allows the study of the influence of the Loire River and the anthropogenic effects on sea level since the 19th century. For instance, Winterwerp *et al.* (2013) showed that the tidal range was strongly modified in upstream areas (Nantes) during the last century because of river deepening, but the impact in downstream locations such as Saint-Nazaire is not yet entirely quantified.

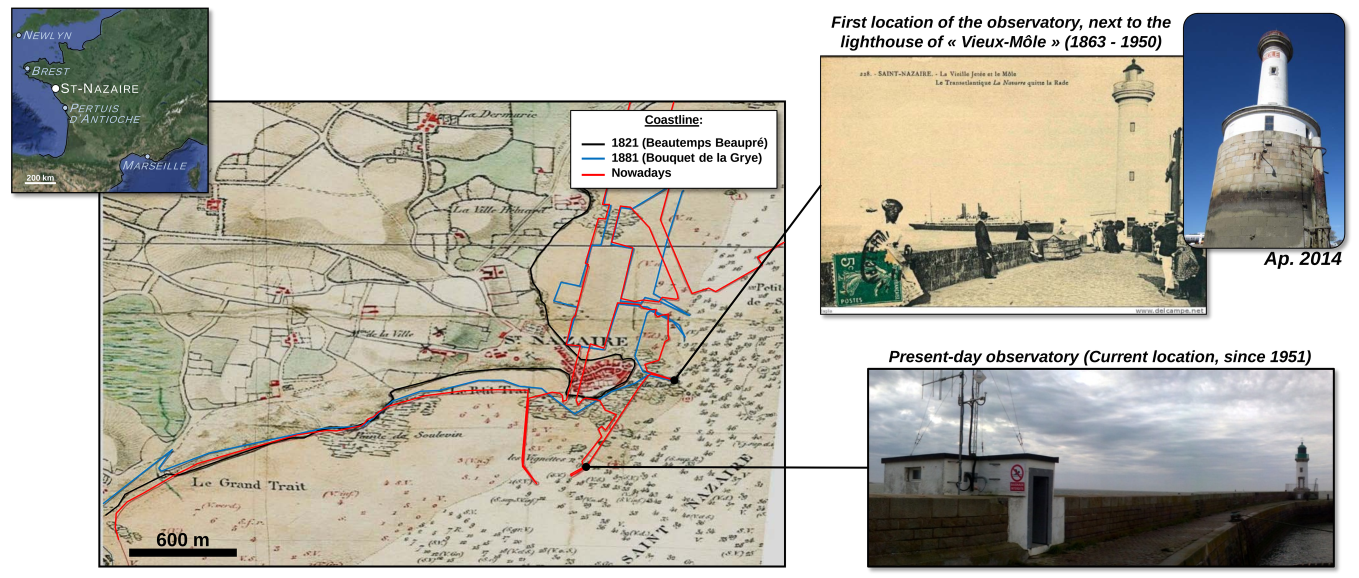


Figure 1: Locations of the Tide Observatory of St-Nazaire and man-induced evolution of the coastline since the 19th century

Sea level measurements over the historical time

As a first and primordial step, **this study implies the inventory of existing sea level observations** which are **scattered in various institutions in France (*Figure 2 & Table 1*).**

The first identified measurements took place **in 1821** for **4.5 months** and correspond to **visual observations at a tide staff** temporarily located in Saint-Nazaire for offshore sounding reduction purpose (background map, ***Figure 1***).

Since 1863 measurements have been **automatically performed** with the use of a **mechanical float tide gauges**. These devices have changed and evolved over the time **allowing measurements up to 2007**, despite the observatory relocation (1951, ***Figure 1***) and some important gaps occurring between 1920 and 1950.

Since 2007, the Saint-Nazaire observatory has been part of the French RONIM network operated by SHOM, and the old mechanical tide gauge has been superseded by a **radar tide gauge** (operated by "Grand Port Maritime" of Nantes-Saint-Nazaire).

The **precious analog dataset** are **handwritten ledgers and/or tidal charts** covering periods ranging between 2 weeks and 1 month. Except the older ones (1821), ledgers correspond to transcripts extracted by observers from tidal charts with a 15-minutes to 1-hour time step.

In total, the covered period is up to 190-year-long, including at least 125 years of continuous sea level measurements.

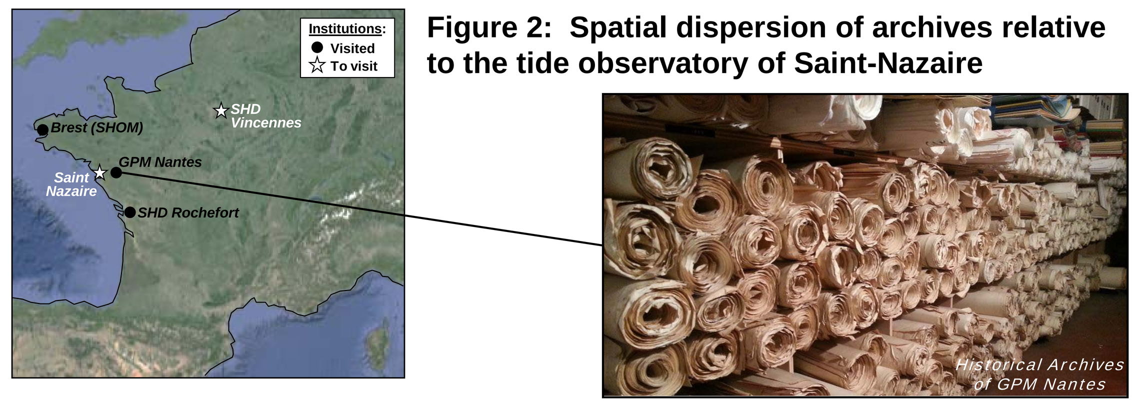
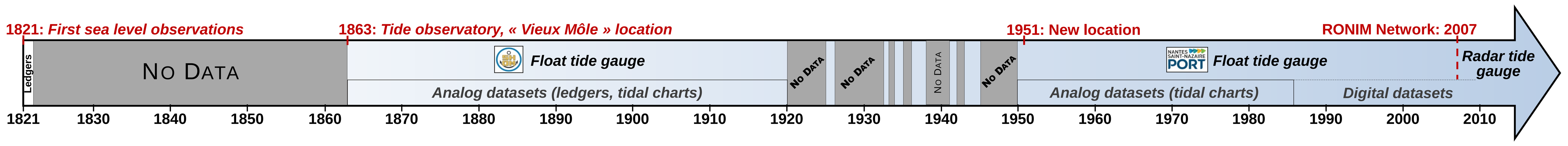


Figure 2: Spatial dispersion of archives relative to the tide observatory of Saint-Nazaire

Table 1: Inventory of available data and characteristics of sea level datasets

Period	Effective duration	Instrument	Sampling strategy	Unit of length	Time system	Type of archive	Historical archive
1821	4.5 months	Tide staff	diurnal-15 min	Foot-Inch	AST	ledgers	SHD (Rochefort)
1863-1894	31 years	Float tide gauge	15 min	metric	AST	ledgers	SHOM (Brest)
1894-1900	6 years	Float tide gauge	15 min	metric	MST	ledgers	SHOM (Brest)
1900-1920	21 years	Float tide gauge	(15 min)	metric	MST	ledgers/tidal charts	SHOM (Brest)
1925	4 months	Float tide gauge	Diurnal-15 min	metric	UT	ledgers	SHD (Rochefort)
1932-1933	3 months	Float tide gauge	(15 min)	metric	UT	tidal charts	GPM Nantes Saint-Nazaire (Port Authority, Nantes)
1934	7 months	Float tide gauge	(15 min)	metric	UT	tidal charts	
1936-1937	23 months	Float tide gauge	(15 min)	metric	UT	tidal charts	
1941	1 year	Float tide gauge	(15 min)	metric	UT	tidal charts	
1943-1944	16 months	Float tide gauge	(15 min)	metric	UT	tidal charts	
1950-1986	37 years	Float tide gauge	(15 min)	metric	UT	tidal charts	
1986-2007	21 years	Float tide gauge	(5 min)	metric	UT	digital tidal charts	
2007-…	7 years …	Radar tide gauge	(5 min)	metric	UT	digital tidal charts	SHOM (Brest)



Reconstruction of the Sea level time serie

Digitization

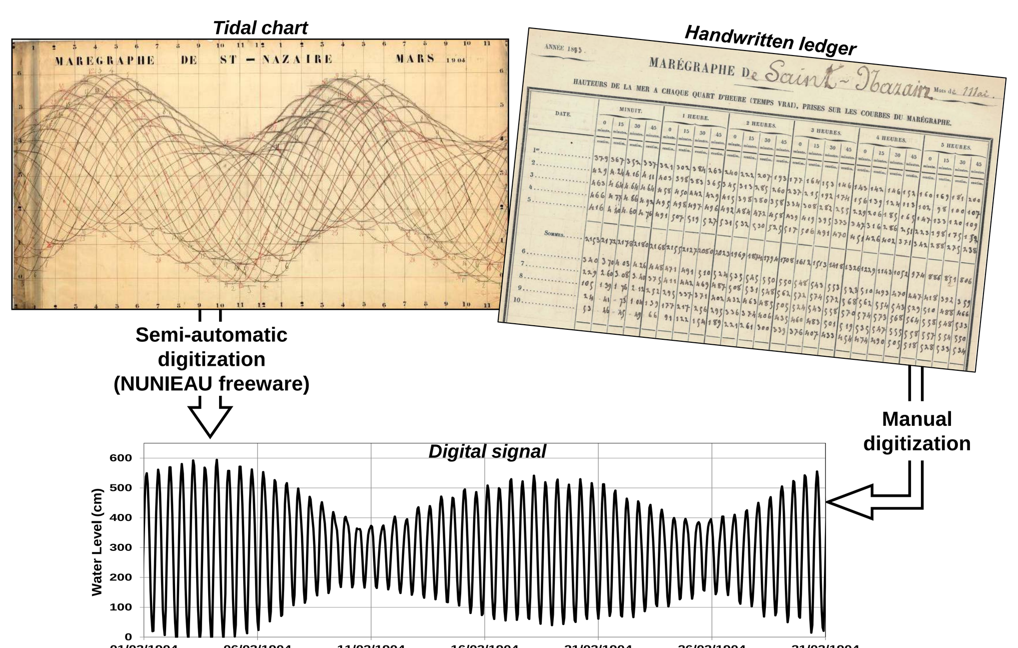


Figure 3: Schematic view of the adopted procedure to digitize the data

In order to make the inventoried datasets available for studying the sea level evolution, **the existing ledgers and tidal charts have to be digitized (*Figure 3*)**.

Handwritten ledgers have been **manually digitized**: about **500.000 hourly values** have been processed. During this **time-demanding work**, **verification procedures** have been set up to **identify errors** related to transcription and/or mistakes made by observers (occuring mostly during the extraction of sea level from tidal chart to ledgers).

Tidal charts are **semi-automatically digitized** by using the NUNIEAU software (Ullmann *et al.*, 2005). **NUNIEAU** is a **signal processing tool based on color recognition**, developed by the CETE Méditerranée (called now, CEREMA) and **free to access.**

Data consistency

A crucial point of this study is to **make these data consistent over time** in **terms of vertical reference and time systems**, which both evolved during the studied period.

As reported in ***Table 1***, the used **time system** is different depending on the considered period: from **Apparent Solar Time (AST)** for oldest datasets to **Mean Solar Time (MST)** to the current **Universal Time (UT)**. In order to get a time continuity, all the data are converted into the UT system: it consists in the application of the "**equation of time**" and a **correction based on the longitude difference between the current location and Greenwich**.

Reducing the reconstructed time serie to a **common vertical reference level** is quite challenging because it implies knowing precisely the different levels used as **tide gauge zero and/or chart datum** over the time (***Figure 4***). To get this information, it is necessary to look through lots of **diverse and scattered documents** (metadata linked to measurements, leveling reports, observers' notes, letters, …). If it is relatively easy to define recent chart datum, it appears to be more difficult for older periods since **much information, sometimes incoherent, have to be analyzed**: in the present state of the research, information concerning the gauge zero between 1890 and 1914 remain rather uncertain.

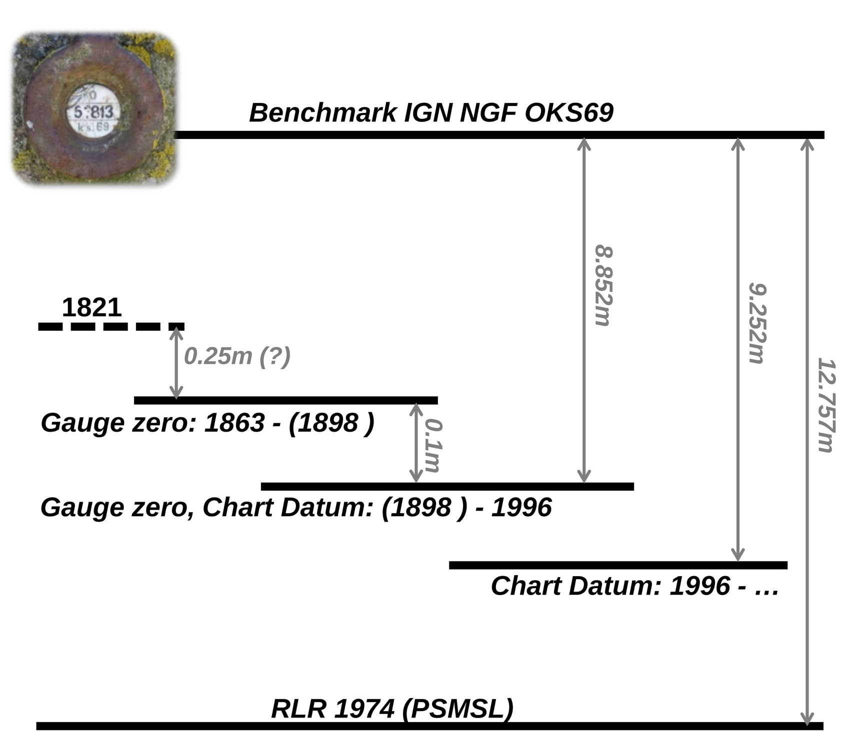


Figure 4: Evolution of the used reference level / Chart datum over the time

Ongoing work / Preliminary results

Long term sea level evolution -- Data quality control

By digitizing this huge amount of sea level data (**about 60 yrs up to now**), the ST Nazaire time serie becomes long enough **to assess the local long-term sea level evolution** and **increase the knowledge at the Northern Europe's scale** (***Figure 5***). However, this is not yet feasible without **first rigorously controlling the data quality**.

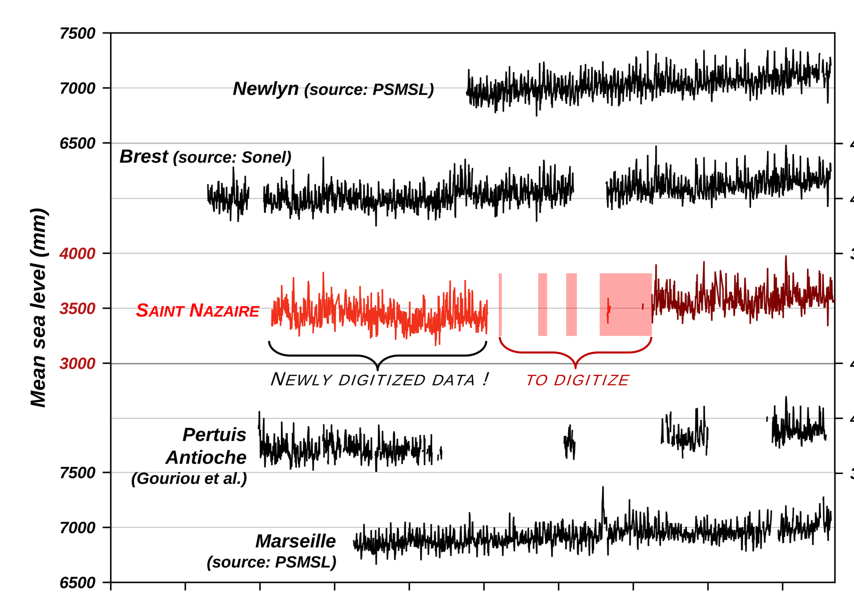


Figure 5: Monthly mean sea level for the Saint-Nazaire time serie (new dataset in light red), and comparison with others long time series from « nearby » stations (*Figure 1*)

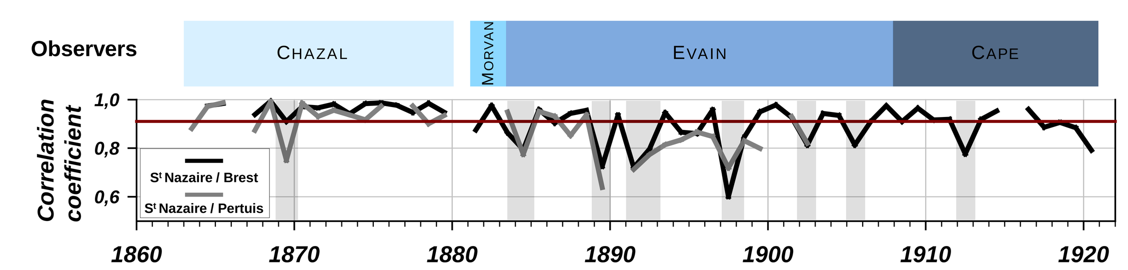


Figure 6: Yearly correlation coefficients between Saint Nazaire sea level time serie and those from « nearby » stations *(red line: correlation coefficient for the modern period)*

The comparison of St-Nazaire, Brest and Pertuis d'Antioche time series proves to be a good method of checking the quality of the newly digitized tide gauge records. On this purpose, **yearly correlation coefficients** have been calculated from monthly mean sea levels (***Figure 6***).

Preliminary results assess **the high quality of the measurements**: most of the time the dataset is characterized by correlation values similar to those obtained on the recent RONIM period (on average, 0.92 and 0.91 with Brest and Pertuis, red line on ***Figure 6***).

Periods showing bad correlation (grey areas, ***Figure 6***) will be **carefully examined** to identify the reasons for this relative bad quality **(vertical offset due to the use of a wrong gauge zero, variable accuracy linked with observers, …)** and to correct it if possible, or reject the data. For this work, **the use of tide predictions will be very useful** as well.

Tidal range evolution

By assuming that vertical offsets occurring between high and low water are limited due to the considered short period, it is possible to study fairly reliably the **evolution of the tidal range in Saint Nazaire** (***Figure 7***).

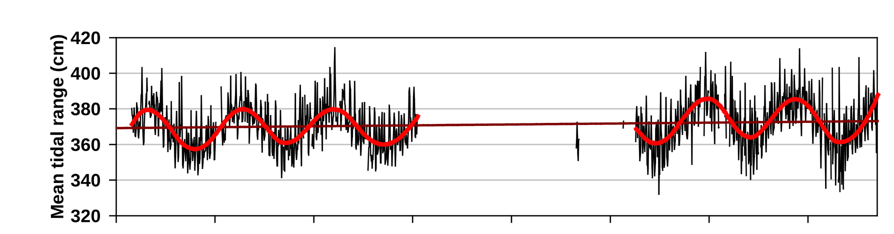


Figure 7: Monthly mean tidal range evolution

Tidal range tends to **slightly increase** over the studied period (**2.5 cm/100 yrs**, linear trend ***Figure 7***) but this is out of proportion with upstream observations. The influence of **the lunar 18.6 year nodal cycle** is clearly visible on the evolution of the tidal range since 1863. It is noticeable that these **long-term oscillations** appear to **increase in amplitude** (red smoothed line ***Figure 7***) with **larger fluctuations**.

This observation could be **due to the man-induced changes** on the area. To verify this potential origin, further analyses are necessary (signal filtering, relations between this evolution and engineering works, …).

Perspectives / Expected outcomes

This presentation overviews **the current status of the study in progress**. Plenty of work is still needed (**keep digitizing tidal charts, rigorous data-quality check,** …) to **get a consistent sea level time series as complete as possible**. Nevertheless, it is already noticeable that **promising results will be achieved**. This type of work highlights **how precious historical data are** because **they are irreplaceable archives making their rescue essential. Atmospheric pressure data**, also available in paper form (1863-1920), could be processed by following the same procedure: a probable better characterization of long-term sea level trend will be reached.

Once the final time-serie has been rendered coherent, it will be made available in existing national databanks and websites: REFMAR for high-frequency data (hourly) and **SONEL for the corresponding mean sea levels** (daily, monthly and yearly).

For further information about this study and his progress, please regularly consult:
http://refmar.shom.fr/en/applications_maregraphiques/programmes-projets/construction-analyse-series-coherentes-niveau-mer/port-de-saint-nazaire

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Acknowledgments

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