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Reconstruction of a two-century long sea level record for the Pertuis d'Antioche (France)

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ABSTRACT

This paper describes the work of sea level data rescue, digitization, reduction to a common vertical reference and quality control leading to the reconstruction of a time series for the Atlantic NW coast of France (Pertuis d'Antioche). A total of 14 sea level data sets were merged to build a consistent composite time series of monthly and annual mean sea levels spanning 188 years (1824–2011).

The estimation of a linear trend for this time series yields a relative mean sea level rise for the region of 1.3 ± 0.1 mm yr^{-1} for the whole study period, and 1.9 ± 0.2 mm yr^{-1} for the 20th century, consistent with previous studies in the region. This work evidences the importance of data archaeology in the pursuing of historical information useful for sea level studies, which can be relevant for climate research and coastal management amongst other applications.

1. Introduction

Within the framework of current concern around climate change, sea level data have become particularly valuable as an indicator of global warming. Nevertheless, there is a scarcity of long time series enabling the estimation of secular trends (Holgate et al., in press). For this reason, considerable efforts have been undertaken to rescue time series of sea level using historical measurements after an arduous process of digitization and quality control (Araujo et al., 2013, Marcos et al., 2011; Raicich, 2007; Testut et al., 2010; Woodworth, 1999; Wöppelmann et al., 2006a). Several works have repeatedly advocated for the pursuing of what is called "data archaeology" so that historical records can be recovered and used (Woodworth et al., 2009; 2010) and a number of initiatives have been launched within the framework of international programmes such as the Global Sea Level Observing System (GLOSS) (Caldwell, 2012; IOC, 2012).

The present work is the result of one of those exercises of data archaeology and takes advantage of the rich history of France concerning sea level observations. According to Cartwright (1999), the oldest French series of sea level observations were recorded as early as 1679 by P. de La Hire and J. Picard at Brest. The aim was to study the ocean tides and the experiment showed the importance of systematic observations to understand and determine the characteristics of the tide in a given place. At the beginning of the 18th century, many sea level observatories were set up along the coasts of France with the support of the 'Académie des Sciences' (Pouvreau, 2008). In the 1840s, the French hydrographic engineer Rémy Chazallon (1802–1872) devised a mechanical instrument (an automatic float gauge) to be used in the first French sea level network which he named 'marégraphe'. French geographical engineers also distinguished themselves in this field (Wöppelmann et al., 2006b), particularly with the invention of a gauge called 'médimarémètre' aimed at measuring the mean sea level directly (Lallemand, 1888), and later on with the development of a method to test the accuracy of mechanical tide gauges by C. van de Casteele (1903–1977) (IOC, 1985).

This manuscript describes the work of rescue, processing and analysis of historical sea level data at the Pertuis d'Antioche, in the region of Charente-Maritime on the west coast of France (Fig. 1). Those historical sea level data have been merged with modern observations in order to obtain a composite time series spanning almost two centuries (1824–2011) representative of the region. The composite time series will be used to study the long-term evolution of relative sea level. This manuscript also intends to serve as reference for further enterprises of the same sort, which we consider to be essential for a better understanding of sea level rise and its potential impacts on the coast. In particular, a special

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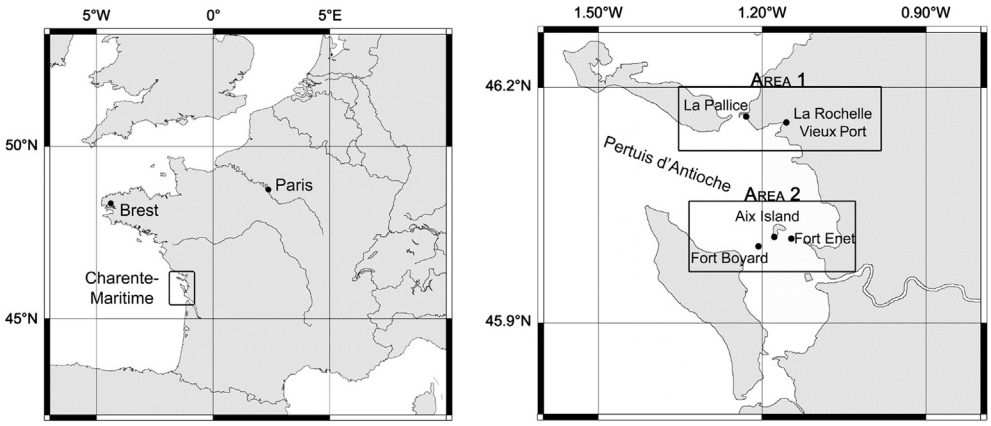

Fig. 1. Maps showing the location of the Pertuis d'Antioche and the sites where the sea level data were recorded.

emphasis will be given to the issue of ensuring the datum continuity, which required an enormous effort. The manuscript is organised as follows:

After the introduction, in Section 2 we present the sea level data sets used for the reconstruction of the Pertuis d'Antioche time series following a chronological order, from the era of visual measurements registered in ledgers to the most modern radar tide gauge data. Section 3 relates to how the data sets were processed and corrected for errors so that they can be considered consistent and eventually merged into one composite time series from different fragments. In Section 4, the final composite time series of daily, monthly and annual sea level means is presented and long-term sea level trends and accelerations are derived. The results are discussed and compared with other estimates in the literature. Finally, some concluding remarks and prospects are outlined in Section 5.

2. Data sets

The sea level data sets used for the reconstruction of the Pertuis d'Antioche composite time series were obtained at six stations in five different locations which belong to two distinct geographical areas. Three stations were part of the two harbour facilities (La Rochelle Vieux Port: internal and external, and La Pallice) near La Rochelle town (Area 1, Fig. 1), whereas the other three were located approximately between 2 and 7 km off the coast, 17 km south of La Rochelle, at two military fortresses (Fort Enet and Fort Boyard) and on Aix Island (Area 2, Fig. 1).

Data sets used in this work begin in 1824. There are also data sets from 1775 to 1776 but they were discarded due to the lack of a reliable vertical reference. Similarly, data sets between 1887 and 1892 were not used in this work as measurements were only taken twice a day (at high waters and low waters) and hourly values were available for that period at Fort Boyard. The main characteristics of each data set are summarized in Table 1 and will next be described in more detail following a chronological order. Their distribution over time is illustrated in Fig. 2.

2.1. Analogue data (1775–1995)

Until the first part of the 19th century, observers took sea level measurements visually at tide scales and they registered down the data by hand in ledgers. Observers worked during the daylight and the sampling strategy varied with the period and the location. Sometimes they took measurements twice a day (at high and low waters) and in other cases every 15 min (see Table 1 for details). In the 1840s, several of the float tide gauges devised by Rémy Chazallon were installed along the French coasts (including our area of interest) inside stilling wells. Chazallon also defined a clear operation procedure which had to be applied at all stations and be strictly followed by the staff, thus improving the quality of the recordings. Sea level measurements taken with the Chazallon tide gauge were automatically registered on paper tidal charts and eventually transcribed by observers to ledgers (Fig. 3) with a sampling period of 15 min. Chazallon tide gauges were still in operation throughout the 20th century, but were progressively replaced by more modern models, also float type.

Handwritten ledgers and the original paper tidal charts used for this work were spread amongst different public and private institutions all around France. Pouvreau (2008) visited those institutions and located the ledgers and tidal charts. Gouriou (2012) accessed the archives, took copies of the documents as photographs, and stored them as images so that they could be digitized manually (Fig. 3). For the purpose of this work only tabulated data (and not the tidal charts) from handwritten ledgers were digitized.

During the Chazallon period, together with sea level measurements other ancillary variables were recorded at Fort Enet (1860–1873), Fort Boyard (1873–1909) and La Rochelle Vieux Port (1863–1874); namely, the atmospheric pressure, wind and air temperature. Atmospheric pressure was measured with a barometer installed in the same hut as the tide gauge. Observers noted down the values six times per day (from 6 am to 9 pm) in ledgers that have also been rescued from the archives and digitized for the purpose of this work. Pressure data were used as an extra quality control check of sea level data as will be described in Section 3.3.

In total, up to 720,000 values of sea level and atmospheric pressure were digitized for this work. This digitization process amounted to approximately 50 weeks of full-time work.

2.2. Digital data (1995 to present)

Over the last two decades, mechanical float gauges in France have been progressively superseded by acoustic and more recently radar tide gauges (Martín Míguez et al., 2008). These new tide gauges provide sea level data in digital form with a sub-hourly sampling range (typically 10 min). In addition to the easier maintenance and stability (Martín Míguez et al., 2012) the higher frequency sampling rate for the radar allows a whole range of new applications such as real-time monitoring within multi-hazard warning systems (storm surges, tsunamis). French digital data are currently available for downloading and visualization in real-time at the REFMAR website (http://refmar.shom.fr/),