

Response to reviewers

11 October 2020

The authors addressed all the comments in the detailed point-by-point responses, that are online since 14 September 2020. In the revised version of the manuscript, the additional changes are as follows:

- 1) There is a substantial increase in the number of long-term station records (18 stations instead of 12):
 - We select now tide gauges with time series starting no later than 1940 (instead of 1930). This led to 4 additional stations: Newport, New London, Wilmington and Fort Pulaski.
 - Two more stations were added in the North Sea: Hoek van Holland and Delfzijl. They were provided by Rijkswaterstaat (RWS). Note that we do not mention anymore the results at Dunkerque and Calais, as Hoek van Holland and Delfzijl are also located in the south of the North Sea, with longer and more interesting time series.
- 2) The statistical model 2 is based on a rigorous multiple linear regression with two parameters, NAO and MSL. The introduction of NAO in model 2 increases its predictive performance, beyond the inherent effect of adding a regression parameter. Indeed, on average, the Akaike Information Criterion (AIC) is 106.3 for model 2, instead of 118.6 for model 1.
- 3) We have moved the nodal modulation part to Appendix A. As it is now in Appendix, we have not shortened the text.

The authors would like to thank the reviewers and Editor for their constructive comments. We tried to do our best to implement them, and we hope that the revised version of the manuscript meets now the high quality standards of Ocean Science.

Climate-scale Large-scale changes of the semidiurnal tide over the North Atlantic coasts from 1846 to 2018

Lucia Pineau-Guillou¹, Pascal Lazure¹, and Guy Wöppelmann²

¹IFREMER, CNRS, IRD, UBO, Laboratoire d’Océanographie Physique et Spatiale, UMR 6523, IUEM, Brest, France

²LIENSS, Université de la Rochelle-CNRS, La Rochelle, France

Correspondence: Lucia Pineau-Guillou (lucia.pineau.guillou@ifremer.fr)

Abstract.

We investigated the long-term changes of the principal tidal component M_2 over the North Atlantic coasts, from 1846 to 2018. We analysed 9 18 tide gauges with time series starting no later than 1920 1940. The longest is Brest with 165 years of observations. We carefully processed the data, particularly to remove the 18.6-year nodal modulation. We found that M_2 variations are consistent at all the stations in the North East Atlantic (Newlyn, Brest, Cuxhaven Cuxhaven, Delfzijl, Hoek van Holland, Newlyn, Brest), whereas some discrepancies appear in the North West Atlantic. The changes started long before the XXth century, and are not linear. The trends in M_2 amplitude vary from a one station to another; they are overall positive, up to 0.7 2.5 mm/yr in the period since 1910. Since 1990, the trends switch from positive to negative values in the North East Atlantic. Concerning the possible causes of the observed changes, the similarity between the North Atlantic Oscillation and M_2 variations in the North East Atlantic suggests a possible influence of the large-scale atmospheric circulation on the tide. Our statistical analysis confirms large correlations at all the stations in the North East Atlantic. We discuss a possible underlying mechanism. A different spatial distribution of water heights level from one year to another, depending on the low-frequency sea-level pressure patterns, could impact the propagation of the tide in the North Atlantic basin. However, the hypothesis is at present unproven.

1 Introduction

Since the XIXth century, tides are Tides have been changing due to non-astronomical factors since the XIXth century (Haigh et al., 2019; Talke and Jay, 2020). In the North Atlantic, secular variations were observed at individual tide gauge stations, e.g. Brest (Cartwright, 1972; Wöppelmann et al., 2006; Pouvreau et al., 2006; Pouvreau, 2008), Newlyn (Araújo and Pugh, 2008; Bradshaw et al., 2016), New York (Talke et al., 2014), Boston (Talke et al., 2018), but also at regional scale, e.g. Gulf of Maine (Doodson, 1924; Godin, 1995; Ray, 2006; Ray and Talke, 2019), North Atlantic (Müller, 2011), and at quasi-global scale (Woodworth, 2010; Müller et al., 2011; Mawdsley et al., 2015). Long-term changes in tidal constituents are rather small at coastal stations, but tend to be statistically significant. The order of magnitude of these changes varies spatially, and may reach few cm/century for M_2 amplitude. For example, Colosi and Munk (2006) reported changes of about 1 cm at Honolulu, Hawaii, between 1915 and 2000. Ray and Talke (2019) found trends varying from -1 to 8 cm/century in the Gulf of Maine

25 over the last century. Woodworth et al. (2010) and Müller et al. (2011) found trends of few % per century in the Atlantic. The changes can be larger at many estuaries and rivers (Talke and Jay, 2020).

The physical causes of these changes ~~are still poorly understood~~ can be multiple and difficult to disentangle. In particular, the complexity comes from the possible interaction between local and large-scale causes. Changes ~~They~~ may have a local scale origin, as changes in the ~~local~~ nearby environment (e.g. harbour development, deepening of channels, dredging, siltation) or changes in the instrumentation (e.g. tide gauge technology, observatory location, instrumental errors). For example, Famikhalili and Talke (2016) show that mean tidal range at Wilmington has doubled since the 1880s, due to channel deepening in the Cap Fear River Estuary. ~~But they~~ Changes may also have a large-scale origin, i.e. regional or global. Haigh et al. (2019) reported several possible large-scale mechanisms: (1) tectonics and continental drift, (2) water depth changes due to mean sea level rise or geological processes such as the Earth's surface glacial isostatic adjustment (Müller et al., 2011; Pickering et al., 2017; Schindelegger et al., 2018), (3) shoreline position, (4) extent of sea-ice cover (Müller et al., 2014), (5) sea-bed roughness, (6) ocean stratification which may modify the internal ~~tides and bottom friction over continental shelves~~ ~~tidal change~~ ~~its surface expression~~ (Müller, 2012), (7) non-linear interactions and (8) radiational forcing (Ray, 2009).

40 Several authors have explored Mean Sea Level (MSL) rise as a potential mechanism to explain M_2 changes. For example, simulations from Pickering et al. (2012) show that a 2m sea level rise could modify M_2 from -20 to 20 cm. Idier et al. (2017) show that depending on the location, the changes can account for +/-15% of the regional sea level rise. Schindelegger et al. (2018) find changes of about 1–5% of the sea level rise. Beyond MSL rise, other mechanisms have been explored to explain M_2 changes. For example, Colosi and Munk (2006) attribute the changes of M_2 amplitude at Honolulu, Hawaii, to a 28° rotation of the internal tide vector in response to ocean warming. Ray and Talke (2019) suggest that long-term changes in stratification could play a role in the Gulf of Maine. Müller (2011) suggests a possible link between M_2 changes and atmospheric dynamics in the North Atlantic; he reported that the timeseries of the North Atlantic Oscillation (NAO) show similar characteristics as those of the tidal amplitudes and phases. In the Gulf of Maine, Pan et al. (2019) suggest that changes in the response of the nodal modulation of the M_2 tide from 1970s to 2013 may be linked with the NAO. In Southeast Asian Waters, Devlin et al. (2018) show that the impact of atmospheric circulation (via the wind stress, through Ekman current) on M_2 seasonal cycle may be significant and comparable to the effect of permanent (geostrophic) currents. In the North Sea, Huess and Andersen (2001) explain a large part of M_2 seasonal cycle by the role of atmospheric dynamics, whereas Müller et al. (2014) and Gräwe et al. (2014) suggest a major role of the thermal stratification. These examples show the diversity of mechanisms that play a role in tide changes. In the present paper, we focus on the role of MSL and atmospheric dynamics.

55

This paper has two main objectives. The first is to characterize the secular changes of the M_2 tide over the North Atlantic. We focus on the longest time series, i.e. starting no later than ~~1920~~1940. This approach is complementary to previous studies investigating M_2 changes focusing on smaller spatial scales, e.g. Brest (Pouvreau et al., 2006; Pouvreau, 2008), Gulf of Maine (Ray, 2006; Ray and Talke, 2019), or focusing on ~~smaller shorter~~ temporal scales, i.e. recent decades (Woodworth, 2010;

60 Müller, 2011). The second objective is to detect if there is any large-scale coherence in the observed changes in the North Atlantic, and investigate the possible link with the atmospheric circulation, already mentioned by Müller et al. (2011), on the basis of qualitative criteria. Here, we further bring quantitative insights on the possible influence of NAO, and discuss a possible NAO-related climate mechanism that can partly explain the observed changes.

65 The paper is organised as follows. The first section describes the data: the sea level data (i.e. tide gauges and their processing) and the atmospheric data (i.e. climate indices and sea level pressure data). The following section presents the results (i.e. M_2 variations and trends). We then discuss a possible link between the observed changes and MSL mean sea level rise, as well as climate indices.

2 Data

70 2.1 Sea level data

2.1.1 Tide gauges selection

The tide gauge data were retrieved from the University of Hawaii Sea Level Center (UHSLC, website accessed April 2020). The dataset consists of 249 stations in the Atlantic Ocean, with hourly sea level observations. Two additional long-term stations - Delfzijl and Hoek van Holland - were provided by Rijkswaterstaat (RWS). The vertical reference level differs from a station to another, which has no impact here, as we focus on tidal components. We apply harmonic analysis on a yearly basis to determine the tidal constituents, thus only a change in the reference level within a year can affect the results.

We selected the stations following three criteria: time series (1) time-series starting before 1920 1940, (2) time-series with at least 80 years with of data, (3) with tidal amplitude significant enough to detect trends, i.e. M_2 amplitude larger than 10 cm. 80 Note that we selected only years with at least 75% of data (see section 2.1.2). Only 1524 stations among the 249 followed the two first criteria (Figure 1). They are all located in the northern hemisphere. On the east side of the North Atlantic, Stockholm, Gedser, Hornbaek, Tregde and Marseille were discarded due to a too small an M_2 amplitude (i.e. lower than 10 cm). These stations are located in the Baltic Sea (Stockholm, Gedser), in the strait separating the Baltic and the North Sea (Hornbaek), in the North Sea (Tregde), and in the Mediterranean Sea (Marseille). On the west side of the North Atlantic, Galveston, Pensacola 85 and Cristobal were also discarded due to a too small a tidal amplitude (i.e. lower than 10 cm). These stations are located in the Gulf of Mexico (Galveston, Pensacola) and the Caribbean Sea (Cristobal).

Finally, 918 stations followed the three criteria detailed above, and were selected for this study (see stations in bold on in Figure 1, 16 stations are from UHSLC, and 2 from RWS). Among them, 35 are located on the North East Atlantic coasts 90 (Newlyn, Brest, Hoek van Holland, Delfzijl and Cuxhaven - note that Hoek van Holland, Delfzijl and Cuxhaven isare located in the North Sea) and 613 are located on the North West Atlantic coasts (Halifax, Eastport, Portland, Boston, Newport, New

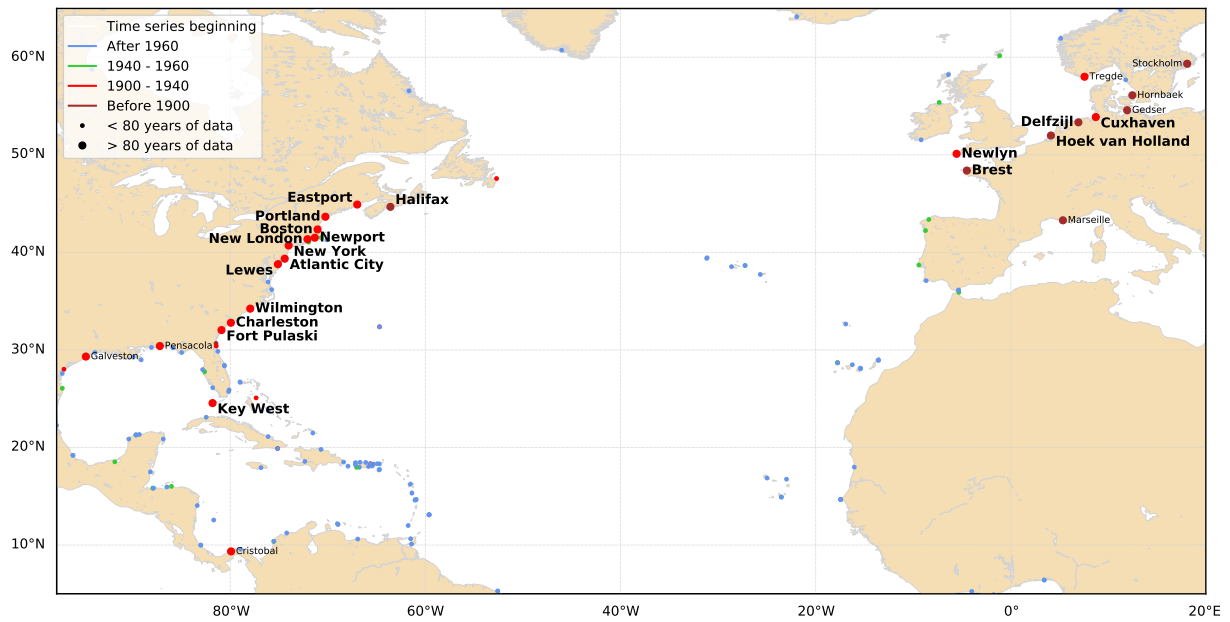


Figure 1. Tide gauges in the North Atlantic. Stations with time series starting before 1920 1940 and longer than 80 years are labelled. Stations selected for this study are in bold.

London, New York, Atlantic City, Lewes, Wilmington, Charleston, Fort Pulaski and Key West).

The main characteristics of the 918 selected stations are synthesised summarised in Table 1. Among them, only Brest, Hoek van Holland and Halifax started in the XIXth century, respectively in 1846, 1879 and 1896 (Table 1, column 2). The number of years with data for each station varies between 8581 and 165 years, Brest being the longest time series (Table 1, column 3).

2.1.2 Data processing

Harmonic analysis was performed in order to compute the M_2 amplitude. We used the MAS program (Simon, 2007, 2013), developed by the French Hydrographic Office (SHOM). This program gives results similar to the T_Tide harmonic analysis toolbox (Pawlowicz et al., 2002) ,largely-used-in-the-scientific-community. For instance, Pouvreau et al. (2006) found non-significant differences on of the yearly amplitudes of M_2 at Brest over the period 1846 to 2005 using T_Tide or MAS. Hourly time series were analysed yearly. Note that at Delfzijl and Hoek van Holland, data had to be interpolated every hour before 1970, as the temporal resolution was of 3 hours. We processed only years with at least 75% of data, to avoid M_2 seasonal modulation. In the North Atlantic, M_2 is affected by a seasonal variation of a few percent (Pugh and Vassie, 1976; Huess and Andersen, 2001; Müller et al., 2014; Gräwe et al., 2014) 180 days, considering that six months was long enough to compute correctly M_2 correctly (Pouvreau et al., 2006). This constraint Considering only years with at least 75% of data resulted in excluding between 1 and 9 up to 15 years, depending on the for a given station (Table 1, columns 3 and 4). Note that in the North Atlantic, M_2 is

Table 1. Main characteristics of tide gauges records selected for this study. Name of the station, timespan, number of years with data, number of years analysed (i.e. with ~~more than 180 days~~ at least 75% of data), ~~MSL average over the period 1910-2010~~, M_2 average amplitude and standard deviation over the period 1910-2010, M_2 nodal modulation, ~~M_2~~ estimated trends in M_2 amplitude since 1910 and since 1990 (standard errors are 1-sigma).

Name	Timespan	Nb of yrs with data	Nb of yrs analysed	$\overline{M_2}$ (cm) [1910-2010]	M_2 nod. mod. f_{nod}	M_2 trends since 1910 (mm/yr)	M_2 trends since 1990 (mm/yr)
Cuxhaven	1918-2018	102	101	135.05 ± 3.68	1.8 %	0.68 ± 0.10	-0.47 ± 0.41
Delfzijl	1879-2018	138	138	125.58 ± 6.96	1.7 %	2.02 ± 0.09	-0.09 ± 0.24
Hoek van Holland	1900-2018	88	82	76.95 ± 2.63	0.8 %	0.85 ± 0.06	-0.45 ± 0.14
Newlyn	1916-2016	102	98	170.66 ± 0.75	3.3 %	0.14 ± 0.02	-0.28 ± 0.14
Brest	1846-2018	165	158	204.54 ± 0.91	3.8 %	0.13 ± 0.02	-0.36 ± 0.12
Halifax	1896-2012	99	95	62.83 ± 0.64	3.7 %	-0.15 ± 0.02	0.32 ± 0.17
Eastport	1930-2018	90	82	263.51 ± 2.50	2.5 %	0.80 ± 0.07	1.01 ± 0.39
Portland	1910-2018	109	104	135.07 ± 1.84	2.8 %	0.56 ± 0.03	0.72 ± 0.20
Boston	1922-2018	98	96	136.57 ± 1.03	2.9 %	0.27 ± 0.03	0.42 ± 0.20
Newport	1931-2018	89	84	50.86 ± 0.41	4.1 %	-0.09 ± 0.01	-0.03 ± 0.08
New London	1939-2018	81	76	35.93 ± 0.25	3.5 %	0.06 ± 0.01	0.03 ± 0.05
New York	1921-2018	95	80	65.13 ± 0.83	3.7 %	0.33 ± 0.02	0.93 ± 0.12
Atlantic City	1912-2018	107	101	58.48 ± 0.31	3.8 %	0.00 ± 0.01	-0.18 ± 0.07
Lewes	1919-2018	85	72	59.91 ± 0.43	3.1 %	-0.06 ± 0.02	-0.33 ± 0.06
Wilmington	1936-2018	84	82	56.84 ± 6.16	1.7 %	2.51 ± 0.09	1.80 ± 0.20
Charleston	1901-2018	101	100	76.40 ± 1.33	3.0 %	0.32 ± 0.03	-0.02 ± 0.08
Fort Pulaski	1936-2018	84	78	100.60 ± 1.01	3.1 %	0.18 ± 0.04	-0.01 ± 0.17
Key West	1913-2018	106	104	17.50 ± 0.36	2.9 %	0.08 ± 0.01	0.13 ± 0.02

affected by a seasonal variation of a few percent (Pugh and Vassie, 1976; Huess and Andersen, 2001; Müller et al., 2014; Gräwe et al., 2014); keeping years with at least 75% of the data (instead of the 50 % here) would allow to avoid this modulation, but would lead to ~~exclude more years~~. We carefully ~~retrieved~~ removed the nodal modulation of M_2 amplitude (Simon, 2007, 2013) , as described briefly in Appendix A. ~~Here is a short description of the method~~. Finally, 3 years were discarded due to problems in the record (1953 and 1962 at Delfzijl, 1953 at Hoek van Holland), and 2 more years due to doubtful M_2 values (1972 at Eastport, 1978 at Newport).

110

115 At all the stations, we computed the normalized M_2 amplitude, removing the average and dividing by the standard deviation over the period 1910-2010

$$\text{Normalized } M_2(t) = \frac{M_2(t) - \overline{M_2}_{[1910,2010]}}{\sigma_{M_2}_{[1910,2010]}} \quad (1)$$

the average $\overline{M_2}$ and standard deviation σ_{M_2} over the 1910-2010 period being given in Table 1 (column 65). The idea is to scale the data, in order to compare all the stations together.

120 2.2 Atmospheric data

2.2.1 Climate indices

We investigated the correlation between secular changes in the tide and climate indices, such as the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO) - also called Northern Annular Mode (NAM) (Hurrell, 1995; Hurrell and Deser, 2009; Thompson and Wallace, 2000; Thompson et al., 2000). These climate indices are related to the distribution of atmospheric masses. They are based on the difference of average sea-level pressure between two centers of actions (i.e. stations), at large time-scale over long periods (e.g. monthly, seasonal, annual).

The NAO is the major pattern of weather and climate variability over the Northern Hemisphere (Hurrell, 1995; Hurrell and Deser, 2009). Variations of NAO are essential, as they drive the climate variability over Europe and North America (Hurrell et al., 2003). We used the wintertime (December to March) Hurrell station-based NAO Index (retrieved from <https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based>). It is based on the difference of normalized average winter sea-level pressure between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland). The normalization consists of removing the long-term mean (1864–1983) and dividing by the long-term standard deviation. The NAO index covers the period 1864-2019, with yearly values.

135

The Arctic Oscillation (AO) is another index which resembles to NAO index. It is defined as the first EOF of northern hemisphere winter sea-level pressure data (Thompson and Wallace, 1998, 2000; Thompson et al., 2000). The AO index is highly correlated with the NAO. We used the wintertime Hurrell AO index (retrieved from <https://climatedataguide.ucar.edu/climate-data/hurrell-wintertime-slp-based-northern-annular-mode-nam-index>). The AO index covers the period 1899-2019.

140

To remove the interannual variability and estimate low frequency variations, climate indices were filtered with a 9-year median mean filter.

2.2.2 Sea level pressure

We explored the Twentieth Century Reanalysis (20CR) (Compo et al., 2011; Slivinski et al., 2019), a historic weather reconstruction from 1836 to 2015, with a 1° gridded global coverage. gridded seasonal sea-level pressure reconstruction from 1750 to

145

2002, covering the eastern North Atlantic, Europe and the Mediterranean area (Küttel et al. (2009), <https://www.nedc.noaa.gov/data-access/>). This 5°X5° gridded dataset is based on ship logs and instrumental pressure series. We computed the mean winter (December to February) sea-level pressure over the period 1850-2002. We averaged from 1850 rather than 1750 (20CR starting date) to be consistent with the temporal coverage of the tide gauges temporal coverage measurements. We also computed yearly anomalies, i.e. removing the average sea-level pressure.

3 Results

3.1 M_2 variations

For the North East Atlantic, the variations of normalized M_2 amplitude are presented in Figure 2 (a).

The first result is that since 1910, the variations between Newlyn, Brest and Cuxhaven are very similar at all the stations. This suggests that these changes are probably due to large-scale processes, rather than local effects due to changes in the environment (e.g. harbor development, dredging, siltation) or instrumentation errors. The high correlation between Brest/Newlyn and Cuxhaven may be surprising, as Cuxhaven is located in the North Sea, (and not in the open Atlantic Ocean), and far away from Brest, (around 1300 km from Brest, compared to 200 km between Brest and Newlyn). This indicates that the spatial scale of the processes responsible for these changes is probably must be at least as large as the North East Atlantic. Different authors noticed the increase of tidal range from 1960 to 1990 in the southern North Sea. Hollebrandse (2005) found a gradual increase during the period 1955-1980 at all the stations of the Dutch coast (5 stations including Hoek van Holland) and the German coast (7 stations). Mudersbach et al. (2013) found a significant increase in M_2 amplitude at Cuxhaven since around the mid-1950s. Note that Cuxhaven is located in the German Bight; shallow depths and shape of the coastline may induce some amplification. Variations in M_2 at Cuxhaven are therefore sensitive to local effects, as the migration of the underwater channels and the evolution of the tidal flats (Jacob et al., 2016). Moreover, Cuxhaven is located in the Elbe estuary, and some river engineering works, as narrowing and deepening, may induce tidal amplification (Winterwerp and Wang, 2013; Winterwerp et al., 2013). Before 1910, M_2 values are higher at Brest than at Delfzijl. This may be explained by the construction of dykes that gradually closed the harbor of Brest since the end of the XIXth century, and may have altered the tide at Brest. To go further, the potential role of these successive constructions needs to be investigated (https://en.wikipedia.org/wiki/Brest_Arsenal). Cartwright (1972) made a first attempt to evaluate the influence of reducing the width of access to the harbour but did not take into account a potential role of dredging for which we have no information. This example underlines the complexity of interpretation of the variations when changes of local and large-scale origin occur at the same time.

The second result, is that there is no linear trends in M_2 variations, but rather break or change points, M_2 increasing and then decreasing, depending on the periods considered. Overall, M_2 increases before 1880, then decreases decreases from 1910 until 1960, increases again until 1980-1990, to finally decrease since 1990; note that the curve is flattening flattens between 1920 and 1940. Pouvreau et al. (2006) yet already noticed these variations at Brest and Newlyn, and suggested a long-period

oscillation of around 140 years, rather than a steady secular trend. A careful analysis of the harmonic development of the tidal potential showed that no tidal component could explain this oscillation. Similarly, no linear combination of tidal harmonic components could explain it (Pouvreau et al., 2006). This suggests that these variations are not due to an astronomical component, but rather linked with changes in the solid Earth-ocean-atmosphere coupling system. Unfortunately, Newlyn and Cuxhaven time series starting only in 1915 and 1918, respectively, do not allow to confirm at large-scale the decrease observed at Brest from 1880 to 1920. However, in contrast to Brest, M_2 at Delfzijl stays flat between 1880 and 1920. The decrease observed at Brest between 1880 and 1920 may be due to harbour development and/or dredging (see above). This underlines the importance of sea level data archaeology, for research studies related to long-term changes (Pouvreau, 2008; Woodworth et al., 2010; Marcos et al., 2011; Talke and Jay, 2013, 2017; Ray and Talke, 2019; Bradshaw et al., 2015, 2020).

The third result is that changes in M_2 have not the same order of magnitude at each station, even if trends are similar (see Figure B1 in Appendix B for time series of M_2). Note that Figure 2 represents normalized M_2 , i.e. removing the average and dividing by the standard deviation. The order of magnitude of (not normalized) M_2 changes are roughly the same at Brest and Newlyn (standard deviations of 0.9 and 0.8 cm, Table 1, column 65), but more than three times larger at Cuxhaven (standard deviation of 3.7 cm), and even larger at Delfzijl (standard deviation of 7 cm). This suggests that Cuxhaven the North Sea may be more sensitive to the processes responsible for these changes. and/or Note also that the environmental setting of Cuxhaven in a semi-closed basin and Delfzijl in the Elbe and Ems estuaries, respectively, could introduce some amplification (e.g. resonance effects, propagation in shallow waters) (Winterwerp and Wang, 2013; Winterwerp et al., 2013).

For the North West Atlantic, the variations of normalized M_2 amplitude are presented on in Figure 2 (b) and (c). We split the stations into two groups, in order to facilitate the detection of patterns. The first feature is that M_2 amplitude varies differently in the North West and in the North East Atlantic. The second is that there are discrepancies between stations, even when close to each other (e.g. Atlantic City and Lewes). We split the stations into two groups, in order to facilitate the detection of patterns, each being consistent in terms of trends: one with globally positive trend (group 1 on Figure 2 (b)), the other one with globally negative or no trend (group 2 on Figure 2 (c)).

The first group (with positive trends) in the North West Atlantic consists of Portland, Charleston and Key West 9 stations (Figure 2 (b)). Three outcomes can be highlighted. The first is that M_2 amplitude globally increases overall since 1900. However, between 1980 and 1990, the three all the stations slightly decrease, and since 1990, only Portland is still increasing significantly they increase again. The second outcome is that the rate of increase is very different from a one station to another (keeping in mind that M_2 is normalized by standard deviation on Figure 2): Portland is increasing 1.4 times faster than Charleston (standard deviations being respectively of 1.82 and 1.33 cm), and 28 times faster than Key West (standard deviation being only of 0.36 cm at Key West). The very slow increase at Key West is due to a small tidal amplitude (i.e. only 17.5 cm of mean amplitude for M_2 , see Table 1, column 6). The large increase in Portland may be explained by some amplification in the Gulf of Maine. In many semienclosed basins, resonance leads to tidal amplification (Talke and Jay, 2020; Haigh et al., 2019). In

the Gulf of Maine, Ray and Talke (2019) reported that the tides in the gulf are in resonance, with a natural resonance frequency close to the N_2 tide (Garrett, 1972; Godin, 1993). Tides may be then very sensitive to any changes in the environment (e.g. basin configuration - shape, depth - but also external forcing). The third outcome, and probably the most interesting one, is related to the values of M_2 at Eastport, Portland and New York in the 1860s in-1864-1865 (134.1 cm), estimated from Ray and Talke (2019) and Talke et al. (2014), and represented (after normalization) as a blue stars on Figure 2 (b). These values are not consistent with the positive linear trend observed at the three stations since 1900, which confirms provides some confirmation of the hypothesis formulated from the Brest analysis: climate-scale variations show some breaks or change points, M_2 increasing and then decreasing, depending on the periods considered. The decrease observed between 1870s and 1920s at the four stations (Brest, Eastport, Portland, New York) suggests a possible large-scale signal, in addition to local processes.

The second group (with negative or no trend) in the North West Atlantic consists of Halifax, Charleston and Key West 4 stations (Figure 2 (c)). Two points can be highlighted. The first is that M_2 globally decreases overall for Halifax, Newport and Lewes, particularly since 1980. This trend is less clear for Atlantic City, which is quite noisy and shows no significant trend. The second point is that at Halifax, M_2 values in 1896-1897 are higher than those after 1920. This suggests that the decrease may have started before the XXth century.

3.2 Estimated trends

We estimated the trends for M_2 amplitude at each station, using linear regression. We computed the trends over two periods: 1910-2018, which corresponds roughly to the whole period of data (except at Brest only 5 stations start before 1910), and 1990-2018, which corresponds to recent decades. Some tests showed that the results were not very sensitive to the start date (moving 1990 to 1985 or 1995). The results are synthesized summarised in Table 1 (columns 8 and 9 7 and 8) and Figures 3 and 4.

The trends estimated from 1910 vary significantly from a one station to another (Figure 3). They are globally positive overall (up to 0.7 mm/yr at Cuxhaven 2.5 mm/yr at Wilmington), which is consistent with previous findings (Araújo and Pugh, 2008; Ray, 2009; Woodworth, 2010; Müller et al., 2011; Ray and Talke, 2019). They are slightly negative at two three stations (Lewes; Halifax, Newport, Lewes), and one station shows no significant trend (Atlantic City). The estimates are statistically consistent with those found previously found by different authors (e.g. 0.15 ± 0.02 mm/yr at Newlyn compared to 0.19 ± 0.03 mm/yr in Araújo and Pugh (2008), 0.56 ± 0.03 mm/yr in Portland, compared to 0.59 ± 0.04 mm/yr in Ray and Talke (2019)). In the North East Atlantic, the trends are consistent with each other, which is not surprising as the stations vary similarly (Figure 2 (a)).

The trends estimated since 1990 are quite different from those estimated since 1910 (Figures 3 and 4), with more stations with negative trends: 69 stations have post-1990 negative trends (Atlantic City, Lewes, Charleston, Brest, Newlyn, Cuxhaven), instead of 2 whereas only 3 stations have post-1910 negative trends (Halifax, Lewes). In the North East Atlantic, they all switch from positive to negative trends. This underlines (1) some recent changes in the latest recent decades (Müller, 2011; Ray and

Talke, 2019) and (2) the difficulty to estimate long-term trends from short records (i.e. less than 30 years), especially if the data are noisy (interannual variability) and the underlying processes non-linear (change points).

250

~~Note that the~~The largest trends are observed in semi-closed basins(~~Cuxhaven in the North Sea, and Portland in the Gulf of Maine~~): Wilmington in the Cape Fear River Estuary, Delfzijl in Ems estuary, Cuxhaven in Elbe estuary, Eastport and Portland in the Gulf of Maine. This suggests a possible amplification due to resonance effects (e.g. Gulf of Maine) and/or propagation in shallow waters (e.g. Cuxhaven), in addition to local effects. The stations located in estuaries or in a harbour with a channel may have been subject to dredging. Channel deepening increases the water depths, which reduces the effective drag, and leads to tidal range amplification. This effect may be particularly large in estuaries (Ralston et al., 2019; Talke and Jay, 2020), and may explain the larger trends at Wilmington (Famikhali and Talke, 2016) and Delfzijl. Finally, the shifting locations of amphidromic points could also play a role (Haigh et al., 2019). In the North Sea, different authors show a possible migration of the present day amphidromes, under a 2 m sea-level rise scenario (Pickering et al., 2012; Idier et al., 2017).

260

The trends have to be interpreted very carefully ~~as the~~ The M_2 variations are not linear, and may increase or decrease depending on the years; as a consequence, the estimated trends depend strongly on the period considered to estimate it. The interannual variability also plays an important role, and when substantial, trends can vary depending on the computational period. For example, at Cuxhaven, the large interannual variability leads to a large uncertainty on the trend computed since 1990 (-0.47 ± 0.41 mm/yr).

265

4 Discussion

4.1 Possible link with mean sea level rise

The MSL ~~Mean sea level~~ rise could partly explain M_2 changes ~~, but is not sufficient to explain alone the secular changes in the tide (Ray and Talke, 2019).~~ Simulations show that ~~mean sea level~~MSL rise impact can result in an change of M_2 up to $\pm 10\%$ of the rise (Pickering et al., 2017; Idier et al., 2017; Schindelegger et al., 2018). ~~Changes are often of the same sign than as mean sea level rise, but sometimes opposite.~~ Schindelegger et al. (2018) show that the sign of the observed M_2 trend is correctly reproduced at 80% of the tide gauges on a global scale, but their simulated trends tend to differ from observations by a factor 3 to 5. Their simulations underestimate the M_2 response to MSL rise in terms of magnitude. Schindelegger et al. (2018) conclude that “magnitudes of observed and modeled M_2 trends are within a factor of 4 (or less) from each other in nearly 50% of the considered cases”. These strong discrepancies between simulations and observations have to be carefully interpreted. (1) Numerical simulations are great tools to perform sensitivity studies and understand processes, but results in quantitative terms may be far from ground truth for many reasons as wide spatial resolution (~ 10 km in Schindelegger et al. (2018)), coarse bathymetry, rough parameterizations, tuning parameters, inadequate forcing, lack of coupling (e.g. with atmosphere). (2) The large discrepancies between the simulations and the observations also strongly suggest that MSL rise is not the only process

275

280 that may explain M_2 changes – other large-scale processes, in addition to local processes, may also play a role.

Figure 5 shows the annual mean sea levels at all the stations, after removing the average over the period 1910-2010 (Table 1, column 5). Mean sea level is rising steadily over all the XXth century, which is not always in line with the changes observed in M_2 amplitude, particularly in the North East Atlantic (Figure 2 (a)). Moreover, global simulations with mean sea level rise suggest that M_2 could increase in the western part of the English Channel (i.e. Brest and Newlyn), and decrease in the southern part of the North Sea (i.e. Cuxhaven) (Pickering et al., 2017). Once again, this is not supported by our observational results, as M_2 varies the same way at these three stations.

Note that mean sea levels The MSL obtained from tide gauges include a solid Earth component as they are referenced to the land. Consequently, if the land is subsiding, mean sea level MSL as observed with a tide gauge will increase (Wöppelmann and Marcos, 2016). Estimates of vertical land motion from SONEL (Système d’Observation du Niveau des Eaux Littorales, www.sonel.org, Santamaría-Gómez et al. (2017)) show that the stations considered here are quite stable or falling slightly in the North East Atlantic (i.e. vertical land movements smaller than 0.5-1 mm/yr). In the North West Atlantic, they are ; but slightly falling more strongly in the North West Atlantic (i.e. trends between -1 and -2 mm/yr) up to -2 mm/yr), with an exception except in the Gulf of Maine, where the land tends slightly to rise. Note that these trends are computed on relatively short periods (i.e. generally < 15 years), making it difficult to infer robust trends over the last century.

Figure 5 shows the annual MSL (after removing the average over the period 1910-2010, and filtering with a 9-year time windows), with and without land movement correction. The correction is applied linearly from SONEL estimates (Santamaría-Gómez et al. (2017) solution), and leads to more consistent MSL trends at the basin scale (Figure 5 (b)). Note that in the following, MSL is systematically corrected for land movement. The correlations between M_2 and MSL indicate that M_2 varies strongly with MSL (see section 4.2). However, M_2 variations show some variability in the North East Atlantic (Figure 2 (a)), which may not be explained with MSL rise alone.

4.2 Possible link with climates indices

305 Other processes than mean sea level MSL rise may impact the tide (see section 1), as : Here, we focus on the atmospheric circulation and the ocean stratification. Ocean and atmosphere are fully coupled, and air-sea fluxes are responsible for the exchange of momentum, water (evaporation and precipitation budget) and heat at their interface. Among the wide range of possible interactions, two mechanisms have been explored for their ability to modify the tide. (1) The momentum flux (wind stress) and the gradient of sea level pressure which acts on the barotropic tide and (2) the water and heat fluxes which induce changes in both temperature and salinity distribution in the ocean. The latter effect acts on the stratification which in turn could impact the tide in two different ways. The first way is the internal tide generation which transfers energy from barotropic and baroclinic motion and modifies surface tidal expression (Colosi and Munk, 2006). However, in the present study, most of the observations comes from coastal stations sheltered by wide continental shelves which dampen internal waves. More

important is the second way: the stratification acts on the eddy viscosity profile by modifying currents profile and bottom drag
 315 over continental shelf, which in turn modify the M_2 surface expression (Kang et al., 2002; Müller, 2012; Katavouta et al.,
 2016). Two mechanisms can modify the tide. (1) The momentum flux (wind stress) and the gradient of sea level pressure
 impact directly the water height; significant change in their low-frequency variability can impact the tide. Hues and Andersen
 (2004) showed that simulations better catch account for the seasonal variability of M_2 , when they are forced with tides and a
 meteorological fields, rather than tides only. (2) The heat fluxes affects directly the ocean stratification. Any change in the
 320 stratification could impact the tide, in two different ways. The first is the internal tide generation which transfers energy from
 barotropic to baroclinic motion (Kang et al., 2002). The second is that stratification acts on the eddy viscosity profile and
 bottom drag over continental shelf and then modifies the M_2 surface expression (Müller, 2012; Katavouta et al., 2016). Ray
 and Talke (2019) suggest a possible role of stratification on secular tidal trends by long-term warming of the Gulf of Maine
 waters. To investigate the relationship between these processes and the observed M_2 changes, we used climate indices that
 325 are relevant to represent them: NAO/AO indices are representative of the atmospheric circulation, and Atlantic Multidecadal
 Oscillation (AMO) index is representative of the sea surface temperature in the North Atlantic.

Here, we focus on the effect of the atmospheric circulation on tide. We used pressure indices (NAO and AO) that are relevant
 to represent atmospheric circulation. The NAO index represents the difference of normalized sea level pressure between the
 330 Azores high pressure system and the Iceland low pressure one (Hurrell, 1995). It indicates the redistribution of atmospheric
 masses between the Subtropical Atlantic and the Arctic (Hurrell and Deser, 2009). ~~As the AO is highly correlated with the
 NAO (Figure 6), in the following, we focus only on the NAO index.~~ In the North East Atlantic, the similarity between the vari-
 ations of the low-frequency winter NAO index (Figure 6) and those of M_2 (Figure 2(a)Figure 6) suggests a possible impact of
 large-scale atmospheric circulation on tide. The NAO index varies from positive to negative phases. Filtering the interannual
 335 variability, NAO tends globally overall to decrease between 1910 and 1970, then increase until 1990, and once again decrease.
 The same way, M_2 amplitude tends to decrease up to 1960, then increase until 1990, and once again decrease. These similar
 patterns raise a possible connection between NAO and M_2 variation, already mentioned by Müller (2011) on the basis of
 qualitative criteria. In the following, we bring quantitative insights on the possible influence of NAO. Yet, this hypothesis is at
 present unproven. It was tentatively proposed by Müller (2011), without providing any description of the physical mechanism,
 340 however. In the following, we develop further this idea.

We computed the correlations (r-value) between normalized M_2 and climate indices, NAO and AO (Figure 7). M_2 , NAO
 and AO are filtered on the same time window (9 years). The correlations are computed since 1910, to have similar periods for
 all the stations. The correlations are considered as significant only if the p-value is lower than 0.05 (95% significance level).
 345 The results are the following: (1) for NAO, 14 stations out of 18 show significant correlation. Note that at Brest, the correlation
 is significant since 1910, but not since 1864 (NAO index used in this study starts only in 1864). This can be explained by
 the M_2 larger amplitude over all the XIXth century, which decreases between 1890 and 1910 (Figure 2 (a)), possibly due to
 harbour development and dykes construction (see section 3.1). (2) In the North East Atlantic, all the stations are positively

correlated with NAO. (3) The strongest correlations (i.e. greater than 0.5) are in the northern part of the North Atlantic, with
 350 strong positive correlations at Cuxhaven and Hoek van Holland, and strong negative correlation at Halifax (-0.55). (4) For AO, we found similar, but overall larger, r-values. This is not surprising as these two indices are highly correlated.

To go further in the relative contribution of MSL and NAO in M_2 variability, we fitted two linear regression models on M_2 variations. In the following, M_2 , MSL and NAO are filtered over 9-year time windows and normalized. We did not consider
 355 stations without M_2 -NAO correlation (Boston, New London, Charleston, Fort Pulaski, black dots on Figure 7). At all the other stations, we fitted M_2 variations with a MSL linear regression model (model 1), and a MSL and NAO multiple linear regression model (model 2). Models 1 and 2 may be expressed as:

$$\text{Model 1} = \alpha_1 \text{MSL} \quad (2)$$

$$360 \quad \text{Model 2} = \alpha \text{MSL} + \beta \text{NAO} \quad (3)$$

The correlations using model 1 (MSL) and model 2 (NAO and MSL) are presented in Figure 8. We checked that there was no significant correlation between NAO and MSL at the stations (there is no correlation at 7 stations, and r-value is between 0.2 and 0.7 at 7 stations, see Figure 8 and discussion below). The results are the following: (1) M_2 varies at first order with MSL (Figure 8). (2) The introduction of NAO (model 2) allows to increase the predictive performance of the model, beyond
 365 the inherent effect of adding a regression parameter. Indeed, on average, the Akaike Information Criterion (AIC) is 106.3 for model 2, instead of 118.6 for model 1. On average, the r^2 -value is 0.65 for model 2 instead of 0.59 for model 1. At some stations, the increase is quite large. For example at Cuxhaven, the r^2 -value jumps from 0.42 to 0.63 between model 1 and 2. (3) The ratio $\frac{\beta}{\alpha+\beta}$ represents roughly the relative NAO contribution compared to the total effect of MSL and NAO (Figure 9), as MSL and NAO are normalized. We found a significant contribution at some stations (e.g. more than 30% at Cuxhaven and
 370 Halifax), whereas negligible at others (e.g. lower than 5% at Portland). 8 stations out of 18 show large NAO contribution (> 20%). The North East Atlantic seems to be more sensitive to NAO. Note that the interpretation of the results is tricky when MSL-NAO correlation is significant (orange bars in Figure 8). For example, at Hoek van Holland, the relative NAO contribution is very small, mainly because MSL and NAO are highly correlated ($r = 0.65$). Figure 10 shows M_2 variations along with the predictions from the two models, at all the stations where the NAO contribution is significant ($\frac{\beta}{\alpha+\beta} > 0.25$) and the
 375 correlation between M_2 and model 2 is large enough ($r > 0.3$). At Cuxhaven, Halifax and Key West, the model 2 (MSL and NAO dependent) better captures the M_2 variations than the model 1 (MSL dependent). The trend-switch observed since the 1990 in the North East Atlantic could be partly explained by the influence of the NAO on the tide.

These results suggest that a NAO-related mechanism may explain part of the variability of M_2 . The underlying mechanism
 380 could be due to the difference of spatial distribution of water heights level, depending on the NAO index. Figure 11 (a) shows

the average sea-level pressure during the period 1850-20022015, derived from ~~a reconstructed sea-level pressure, from ship logs and measurements (Küttel et al., 2009)~~ the Twentieth Century Reanalysis (20CR) (Compo et al., 2011; Slivinski et al., 2019). A positive NAO ~~year~~ winter (e.g. 1989) corresponds to a situation with a stronger gradient pressure than average, between the two pressure systems of Azores and Iceland (Figure 11 (c)). By contrast, a negative NAO ~~year~~ winter (e.g. 1969) corresponds to a weaker gradient pressure than usually (Figure 11 (b)). This way, from one year to another, the large-scale atmospheric masses are ~~differently~~ distributed ~~differently~~, and as a consequence, the water volumes are also ~~differently~~ distributed ~~differently~~ in the Northern Atlantic. In a situation of NAO⁺, the ~~surface~~ waters are pushed ~~southern~~ onshore, moving from Iceland to the European coasts of France, Spain and Portugal. Figure 12 (a) shows the redistribution of the ~~water volumes~~ sea-level pressure, between two years with high and low NAO indices (here 1989 and 1969). Note that this is an extreme situation, as these years have strong positive and negative indices. The ~~impact changes~~ in terms of water ~~height level~~ may vary from ~~-21 cm to 12 cm, -15 cm to 24 cm, assuming an inverse barometer response of sea level~~. This variation of a few tens of cm is probably negligible offshore, but may have some impact on tide propagation along the continental shelves and in shallow waters. It could also shift slightly the amphidromic points. Assuming that these changes have a similar impact (in terms of magnitude) on M_2 as ~~mean sea-level MSL changes~~, that is, $\pm 10\%$ in shallow waters according to recent simulations (Pickering et al., 2017; Idier et al., 2017), we find that they can yield changes in M_2 amplitude up to a few centimeters. In other words, their order of magnitude is in agreement with the changes observed in M_2 (Table 1).

We conducted further investigations to test if the magnitude of sea-level pressure changes induced by large-scale atmospheric circulation (Figure 12 (a), few tens of hPa) can generate the observed decadal-scale M_2 changes at Cuxhaven (Figure 12 (b), few cm). Note that M_2 changes due to large-scale atmospheric circulation are only a small part of the total observed changes (20 cm at Cuxhaven), as the changes are also due to MSL rise. The underlying mechanism invoked in the present paper (i.e. the influence of the atmospheric circulation on the tide) is very close to the one described in Huess and Andersen (2001), except that we are considering a longer time scale (decadal instead of seasonal). Huess and Andersen (2001) explain partly M_2 seasonal variations through the effect of atmospheric circulation. They run a barotropic model in the North Sea, forced (1) with tides only and (2) with both tides and meteorological fields. Their results show that the M_2 seasonal modulation is better captured when the model is forced with both tides and meteorological fields (their Figure 2, top right, amplitude higher than 10 cm in the German Bight) rather than with tides only (their Figure 2, top left, amplitude lower than 5 cm in the German Bight). It is important to underline that their model is barotropic, and that there is no effect of stratification, which may also play a role in M_2 changes (see 3.3.6 in the review of Haigh et al. (2019)). At seasonal scale, we computed monthly (instead of yearly) M_2 variations at Cuxhaven over 5 years (2010-2015), and we obtained results in agreement with Huess and Andersen (2001). That is, a seasonal cycle with a range of around 15 cm, maximum in summer and minimum in winter (Figure 12 (d)). According to Huess and Andersen (2001), this seasonal cycle is partly due to the atmosphere circulation. We then computed the differences of monthly sea-level pressure between January and July 2015 (Figure 12 (c)), and obtained values close to the ones in Figure 12 (a). This shows that the order of magnitude of sea-level pressure changes between a NAO⁺ and NAO⁻ years (Figure 12 (a), few tens of hPa) may lead to the M_2 observed changes at Cuxhaven (Figure 12 (b), few cm). The assumption

that changes of few tens of hPa in the Northern Atlantic may generate a sea level response of few centimeters is reasonable, but dedicated simulations should be conducted to confirm or discard the water volumes redistribution hypothesis. Note that here, we followed the hypothesis mentioned in Huess and Andersen (2001), who consider that the atmospheric circulation may be partly responsible of M_2 seasonal variations in the North Sea. But there are other hypotheses; Müller et al. (2014) and Gräwe et al. (2014) rather consider that the stratification plays a major role in the North Sea. However, it is difficult to disentangle the respective contribution of each of these two processes in M_2 seasonal changes, only from the available observations.

Finally, note that NAO variability results not only in sea-level pressure change, but also wind stress, air surface temperature and precipitations (Visbeck et al., 2001). Large changes in winds at on the scale of the Atlantic could also play a role.

In the North West Atlantic, there is no clear similarity between the NAO index and the variations of M_2 . Only the decrease of M_2 since 1990 at Halifax and Atlantic City may reveal a potential link with the NAO, as this index decreases since 1990.

Finally, we investigated the link between M_2 variations and AMO. The AMO index is defined as the average sea surface temperature in the North Atlantic, detrended to isolate the natural variability (Enfield et al., 2001). However, we did not find any clear relationship. This index shows an oscillation with a period of around 70 years (Schlesinger and Ramankutty, 1994; Enfield et al., 2001). Since 1856, the lowest indices (i.e. the coldest lowest sea surface temperatures periods) were observed in 1900-1920 and 1970-1990, which is not consistent with the observed M_2 variations.

5 Conclusions

We investigated the long-term changes of the principal tidal component M_2 over the North Atlantic coasts. We analysed 9 18 tide gauges with time series starting no later than 1920 1940. The longest is Brest with 165 years of data. We carefully processed the data, particularly to remove the 18.6-year nodal modulation.

We found that M_2 variations were consistent at all the stations in the North East Atlantic (Newlyn, Brest, Cuxhaven Cuxhaven, Delfzijl, Hoek van Holland, Newlyn, Brest), whereas some discrepancies appear in the North West Atlantic. The changes started long before the XXth century, and are not linear. The trends vary significantly from a station to another; they are overall positive, up to 0.7 2.5 mm/yr, or slightly negative. Since 1990, in many stations, the trends switch from positive to negative values. The significant differences between the trends since 1910 and 1990 calls for indicate caution when interpreting trends based on short records, i.e. less than 30 years, especially if the data are noisy (interannual variability) and the underlying processes non-linear (change points).

Concerning the causes of the observed changes, M_2 varies primarily with the MSL, but MSL the mean sea level rise is not sufficient to explain alone the variations alone. The similarity between the North Atlantic Oscillation and M_2 variations

in the North East Atlantic suggests a possible influence of the large-scale atmospheric circulation on the tide. Our statistical analysis confirms large correlations at all the stations in the North East Atlantic. The trend-switch observed since 1990 could be the signature of the large-scale atmospheric circulation on M_2 tide. The underlying mechanism would be a different spatial distribution of water heights level from one year to another, depending on the low-frequency sea-level pressure patterns, and impacting the propagation of the tide in the North Atlantic basin. In the future, dedicated modelling studies should be undertaken to confirm or discard this hypothesis. These simulations should also allow to estimate the effect of the wind (through the Ekman current) and the currents on M_2 changes (Devlin et al., 2018).

In this study, we focused only on M_2 amplitude. A similar analysis on the phase lag would draw a more complete picture of the M_2 variations (Müller, 2011; Woodworth, 2010; Ray and Talke, 2019). Other constituents are also affected. Results show that S_2 amplitude decreases at all the stations located in the North West Atlantic, and in contrast, tend to increase in the North East Atlantic (not shown). The large-scale decrease of S_2 observed in the North West Atlantic is consistent with previous studies, e.g. Ray (2006) in the Gulf of Maine. Further investigations should be definitely conducted to extend this work to more constituents.

One of the major findings of this work is The historic data show that the changes started long before the XXth century. This conclusion would not have been possible without the huge work of data rescue undertaken over the past decades (e.g. Pouvreau et al., 2006; Pouvreau, 2008; Bradshaw et al., 2016). This underlines the great importance of sea level data archaeology, which allows to extend and improve historical datasets (Pouvreau, 2008; Woodworth et al., 2010; Marcos et al., 2011; Talke and Jay, 2013, 2017; Ray and Talke, 2019; Bradshaw et al., 2015, 2020; Haigh et al., 2019). This is essential for studies related to climate change.

Finally, we should mention several additional limitations and perspectives in this study. ~~(1) We considered years with at least 50% of data. However, M_2 is affected by a seasonal variation of a few percent (Müller et al., 2014). Keeping years with at least 75% of the data would allow to avoid this modulation—but would lead to exclude more years.~~ (2) (1) We processed the time series downloaded from the database, considering that they were quality controlled. A deep fuller analysis of the data quality before processing would probably be valuable. (3) (2) We did not investigate the history of each station. There are probably some local changes (e.g. environment or instrumentation) that may explain a part of the variability of M_2 amplitude, and some discrepancies between stations. (4) (3) The tide gauges are located on the coast, and mainly in harbours. They are affected at the same time by local and regional/global scale changes, that are difficult to separate. Moreover, they may be not representative of changes offshore. A similar study based on satellite altimetry data would probably be of great interest, even if temporal scale for satellite data is still rather short (i.e. < 30 years) compared to climate-scale processes. (4) We focused mainly on the UHSLC dataset, which consists of 249 stations in the Atlantic Ocean. Other relevant stations (that are not in this dataset) may be considered in future studies, among them on the US coast Sandy Hook and Long Island Sound (Kemp et al., 2017). (5) We did not investigate the impact of storminess on tide. Dedicated studies are necessary to estimate if changes in storminess could

485 affect significantly tidal constituents. (6) We used only winter AO and NAO indices, which show more variability than annual indices. A similar analysis with annual indices shows similar results for the correlation with AO or NAO (positive correlation on the North East Atlantic). With annual rather than monthly indices, the difference of pressure fields will decrease, and as a consequence, the magnitude of the sea-level response will also decrease. Further investigations should be conducted on this point.

490 Appendix A: Nodal modulation

The M_2 component is subject to a 18.6-year modulation, ~~when poorly~~ separated from a neighboring ~~component line in the tidal potential~~. ~~Indeed, M_2 is very close in terms of frequency to another component (m_2) whose Doodson number differs only from the in its 5th figure frequency (255 555 and 255 545 for M_2 and m_2 , respectively) (Doodson and Warburg, 1941; Pugh and Woodworth, 2014).~~ This 5th figure frequency corresponds to N' , the ~~opposite negative of the~~ mean longitude of the Moon ascending node - hence the "nodal" term - whose period is 18.6 years. Note that there is also another component close to M_2 , whose Doodson number differs only from the 5th figure frequency (255 565), but it is negligible, ~~as~~ its amplitude in the tidal potential ~~is being~~ only 0.05% of M_2 , whereas m_2 amplitude is 3.7 % of M_2 (Simon, 2007, 2013). With one year of hourly data, the two components M_2 and m_2 ~~are not correctly~~ cannot be separated ~~with a~~ by a yearly harmonic analysis (at least 18.6 years are necessary). As a consequence, M_2 amplitude is modulated by m_2 . However, we can estimate this modulation, and
500 remove it. The harmonic formulation is expressed ~~schematically~~ as a sum of harmonic components

$$h(t) = \sum_i a_i \cos(V_i(t) - \kappa_i) \quad (\text{A1})$$

where $h(t)$ is the sea level height at time t , $V_i(t)$ is the astronomical argument (computed from Doodson number) and a_i , κ_i the amplitude and phase ~~shift lag~~ of each component. Considering that M_2 and m_2 are very close in terms of frequency, we can assume that their phase ~~shift lags~~ are similar ($\kappa_{M_2} \simeq \kappa_{m_2}$). As their difference of astronomical arguments is $V_{m_2} - V_{M_2} =$
505 $N' + \pi$, the M_2 and m_2 contributions to the total water level may be expressed as

$$h_{M_2}(t) + h_{m_2}(t) = h_{M_2}(t)[1 + f_{nod} \cos(N' + \pi)] \quad (\text{A2})$$

where f_{nod} , the nodal modulation, is the ratio of the amplitude of m_2 and M_2 . As M_2 and m_2 are very close in terms of frequency, f_{nod} is generally considered as close to the ratio of their amplitude in the tidal potential, A_{m_2} and A_{M_2}

$$f_{nod} = \frac{a_{m_2}}{a_{M_2}} \simeq \frac{A_{m_2}}{A_{M_2}} \simeq 0.037. \quad (\text{A3})$$

510 The ~~opposite negative~~ of the mean longitude of the Moon ascending node is ~~simply~~ expressed ~~simply~~ as a function of time (p. 116 in Simon (2007), p. 112 in Simon (2013))

$$N' = -N = 234.555 + 1934.1363T + 0.0021T^2 \quad (\text{A4})$$

with N' in degrees, and T the time elapsed since 2000/01/01 at 12:00, expressed in Julian centuries (36 525 days).

515 The tidal program we used (MAS) corrected M_2 applying the usual 3.7% nodal modulation (Eq. (A3)). However, this value may vary significantly from ~~a one~~ station to another; Ray (2006) reported values ranging from 2.3 % to 3.6 % in the Gulf of Maine. Here, we computed directly f_{nod} from the observed data, proceeding as follows. (1) We added ~~the~~ default nodal correction $1 + 0.037\cos(N' + \pi)$ to the M_2 variations. (2) We detrended the obtained signal removing the last Intrinsic Mode Function (IMF) of an Empirical Mode Decomposition (EMD) (Huang et al., 1998); note that the EMD is an analysis tool which
520 partitions a series into 'modes' (i.e. IMFs), the last one being the trend of the signal. (3) We fitted a function $a_{m_2}\cos(N' + \pi)$ ~~on~~ to this detrended signal to estimate a_{m_2} , N' being expressed as in Eq. (A4). (4) We finally computed f_{nod} as the ratio between m_2 and M_2 amplitudes (Eq. (A3)). Figure A1 (a) shows an example of estimate of M_2 modulation at Newlyn: the fit leads to a nodal modulation of 3.3 %. Note that this value is consistent with Woodworth (2010) (3.2 %), whereas Woodworth et al. (1991) gave a slightly different value (2.8 %). Figure A1 (b) shows the impact of this value rather than the default one:
525 oscillations of 18.6 years are clearly reduced. Note that in this study, the m_2 amplitude - and then the nodal correction - could have been computed from the full time series harmonic analysis, as records are longer than 18.6 years. However, the method presented here to compute the nodal correction, can be applied even for time series shorter than 18.6 years.

The computed nodal modulations are ~~synthesised summarised~~ in Table 1 (column ~~76~~). They vary from ~~1.8 to 3.8~~ 0.8 to 4.1
530 %. Note that these values are consistent with those obtained by previous authors (Ray, 2006; Müller, 2011; Woodworth, 2010; Ray and Talke, 2019). Only the value at Charleston differs significantly: - 3.0 % in our study compared to 3.7% in Müller (2011).

Appendix B: Time series of annual M_2 amplitude at all the stations

535 *Author contributions.* LPG analysed the data and wrote the paper. PL and GW contributed to the interpretation of the data and the writing of the paper.

Competing interests. The authors declare no competing interests.

Acknowledgements. This work was supported by the Research Theme "Long-term observing systems for ocean knowledge" of the ISblue project "Interdisciplinary graduate school for the blue planet", co-funded by a grant from the French government under the program "Investissements d'Avenir" (ANR-17-EURE-0015). The sea level observations were provided by the University of Hawaii Sea Level Center - retrieved from <ftp://ftp.soest.hawaii.edu/uhslc/rqds>, accessed April 2020. The sea level data at Delfzijl and Hoek van Holland were provided by Rijkswaterstaat (RWS) Service Desk, Netherlands. The climate indices (NAO and AO indices) were provided by the the Climate Analysis Section, NCAR, Boulder, USA - retrieved from <https://climatedataguide.ucar.edu/climate-data/>, accessed April 2020. The AMO index was provided by NOAA Physical Sciences Laboratory - retrieved from <https://psl.noaa.gov/data/timeseries/AMO/>, accessed April 2020. The sea-level-pressure reconstruction from Küttel et al. (2009) was provided by World Data Center for Paleoclimatology, Boulder and NOAA Paleoclimatology Program (retrieved from <https://www.ncdc.noaa.gov/data-access/paleoclimatology-data> accessed March 2020). The estimates of vertical land motion were retrieved from SONEL (www.sonel.org, accessed April 2020). The harmonic analysis program MAS was provided by the French Hydrographic Office (SHOM). Support for the Twentieth Century Reanalysis Project version 3 dataset was provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory. The authors warmly thank P. Woodworth for his helpful comments. The authors very warmly thank the two reviewers (Stefan Talke and an anonymous reviewer) and the Editor (Philip Woodworth) for their careful reading and their many constructive comments, which allowed to greatly improve the paper.

References

- Araújo, I. B. and Pugh, D. T.: Sea levels at Newlyn 1915–2005: Analysis of trends for future flooding risks, *Journal of Coastal Research*, 24, 203–212, <https://doi.org/10.2112/06-0785.1>, 2008.
- Bradshaw, E., Rickards, L., and Aarup, T.: Sea level data archaeology and the Global Sea Level Observing System (GLOSS), *GeoResJ*, 6, <https://doi.org/10.1016/j.grj.2015.02.005>, 2015.
- Bradshaw, E., Woodworth, P., Hibbert, A., Bradley, L., Pugh, D., Fane, C., and Bingley, R.: A century of sea level measurements at Newlyn, Southwest England, *Marine Geodesy*, 39, 115–140, <https://doi.org/10.1080/01490419.2015.1121175>, 2016.
- Bradshaw, E., Ferret, Y., Pons, F., Testut, L., and Woodworth, P.: Workshop on Sea Level Data Archaeology, Paris, France, 10 – 12 March 2020, Tech. rep., Intergovernmental Oceanographic Commission, Workshop Report No. 287, 2020.
- Cartwright, D. E.: Secular changes in the oceanic tides at Brest, 1711–1936, *Rev. of Geophys.*, 57, 433–449, <https://doi.org/10.1111/j.1365-246X.1972.tb05826.x>, 1972.
- Colosi, J. A. and Munk, W.: Tales of the Venerable Honolulu Tide Gauge, *J. Phys. Oceanogr.*, 36, 967–996, <https://doi.org/10.1175/JPO2876.1>, 2006.
- Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J.: The Twentieth Century Reanalysis Project, *Quart. Journ. Roy. Meteorol. Soc.*, 137, 1–28, <https://doi.org/10.1002/qj.776>, 2011.
- Devlin, A. T., Zaron, E. D., Jay, D. A., Talke, S. A., and Pan, J.: Seasonality of tides in Southeast Asian Waters, *J. Phys. Oceanogr.*, 48, 1169–1190, <https://doi.org/10.1175/JPO-D-17-0119.1>, 2018.
- Doodson, A. T.: Perturbations of harmonic tidal constants, *Proceedings of the Royal Society*, 106, 513–526, <https://doi.org/10.1098/rspa.1924.0085>, 1924.
- Doodson, A. T. and Warburg, H. D.: *Admiralty Manual of Tides*, HMSO, London, U.K., 1941.
- Familkhalili, R. and Talke, S. A.: The effect of channel deepening on tides and storm surge: A case study of Wilmington, NC, *Geophys. Res. Lett.*, 43, 9138–9147, <https://doi.org/10.1002/2016GL069494>, 2016.
- Garrett, C.: Tidal resonance in the Bay of Fundy and Gulf of Maine, *Nature*, 238, 441–443, <https://doi.org/10.1038/238441a0>, 1972.
- Godin, G.: On tidal resonance, *Continental Shelf Research*, 13, 89–107, [https://doi.org/10.1016/0278-4343\(93\)90037-X](https://doi.org/10.1016/0278-4343(93)90037-X), 1993.
- Godin, G.: Rapid evolution of the tide in the Bay of Fundy, *Continental Shelf Research*, 15, 369–372, [https://doi.org/10.1016/0278-4343\(93\)E0005-S](https://doi.org/10.1016/0278-4343(93)E0005-S), 1995.
- Gräwe, U., Burchard, H., Müller, M., and Schuttelaars, H. M.: Seasonal variability in M2 and M4 tidal constituents and its implications for the coastal residual sediment transport, *Geophys. Res. Lett.*, 41, 15 563–5570, <https://doi.org/10.1002/2014GL060517>, 2014.
- Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., Hill, D. F., Horsburgh, K., Howard, T., Idier, D., Jay, D. A., Jänicke, L., Lee, S. B., Müller, M., Schindelegger, M., Talke, S. A., Wilmes, S., and Woodworth, P. L.: The tides they are a-changin’: A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms and future implications, *Rev. of Geophys.*, 57, e2018RG000 636, <https://doi.org/10.1029/2018RG000636>, 2019.
- Hollebrandse, F.: Temporal development of the tidal range in the southern North Sea, Tech. rep., Master thesis, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2005.

- Huang, N. E., Shen, Z., Long, S. R., Wu, M. C., Shih, H. H., Zheng, Q., Yen, N.-C., Tung, C. C., and Liu, H. H.: The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis, *Proc. R. Soc. Lond. A*, 454, 903–995, <https://doi.org/10.1098/rspa.1998.0193>, 1998.
- Huess, V. and Andersen, O. B.: Seasonal variation in the main tidal constituent from altimetry, *Geophys. Res. Lett.*, 28, 567–570, <https://doi.org/https://doi.org/10.1029/2000GL011921>, 2001.
- Hurrell, J.: Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation, *Science*, 269, 676–679, <https://doi.org/10.1126/science.269.5224.676>, 1995.
- Hurrell, J., Kushnir, Y., Ottersen, G., and Visbeck, M.: An overview of the North Atlantic oscillation, *Geophys. Monogr. Ser.*, 134, 1–36, <https://doi.org/10.1029/134GM01>, 2003.
- Hurrell, J. W. and Deser, C.: North Atlantic climate variability: The role of the North Atlantic Oscillation, *Journal of Marine Systems*, 78, 28–41, <https://doi.org/10.1016/j.jmarsys.2008.11.026>, 2009.
- Idier, D., Paris, F., Cozannet, G. L., Boulahyaa, F., and Dumas, F.: Sea-level rise impacts on the tides of the European Shelf, *Continental Shelf Research*, 137, 56–71, <https://doi.org/10.1016/j.csr.2017.01.007>, 2017.
- Jacob, B., Stanev, E. V., and Zhang, Y. J.: Local and remote response of the North Sea dynamics to morphodynamic changes in the Wadden Sea, *Ocean Dynamics*, 66, 671–690, <https://doi.org/10.1007/s10236-016-0949-8>, 2016.
- Kang, S. K., Foreman, M. G. G., Lie, H. J., Lee, J. H., Cherniawsky, J., and Yum, K. D.: Two-layer tidal modeling of the Yellow and East China Seas with application to seasonal variability of the M2 tide, *J. Geophys. Res. Oceans*, 107, 3020, <https://doi.org/10.1029/2001JC000838>, 2002.
- Katavouta, A., Thompson, K. R., Lu, Y., and Loder, J. W.: Interaction between the tidal and seasonal variability of the Gulf of Maine and Scotian shelf region, *J. Phys. Oceanogr.*, 46, 3279–3298, <https://doi.org/10.1175/JPO-D-15-0091.1>, 2016.
- Kemp, A. C., Hill, T. D., Vane, C. H., Cahill, N., Orton, P. M., Talke, S. A., Parnell, A. C., Sanborn, K., and Hartig, E. K.: Relative sea-level trends in New York City during the past 1500 years, *The Holocene*, 27, 1169–1186, <https://doi.org/10.1177/0959683616683263>, 2017.
- Marcos, M., Puyol, B., Wöppelmann, G., Herrero, C., and García-Fernández, M. J.: The long sea level record at Cadiz (southern Spain) from 1880 to 2009, *J. Geophys. Res.*, 116, C12 003, <https://doi.org/10.1029/2011JC007558>, 2011.
- Mawdsley, R. J., Haigh, I. D., and Wells, N. C.: Global secular changes in different tidal high water, low water and range levels, *Earth’s Future*, 3, 66–81, <https://doi.org/10.1002/2014EF000282>, 2015.
- Mudersbach, C., Wahl, T., Haigh, I. D., and Jensen, J.: Trends in high sea levels of German North Sea gauges compared to regional mean sea level change, *Continental Shelf Research*, 65, 111–120, <https://doi.org/10.1016/j.csr.2013.06.016>, 2013.
- Müller, M.: Rapid change in semi-diurnal tides in the North Atlantic since 1980, *Geophys. Res. Lett.*, 38, L11 602, <https://doi.org/10.1029/2011GL047312>, 2011.
- Müller, M.: The influence of changing stratification conditions on barotropic tidal transport and its implications for seasonal and secular changes of tides, *Continental Shelf Research*, 47, 107–118, <https://doi.org/10.1016/j.csr.2012.07.003>, 2012.
- Müller, M., Arbic, B. K., and Mitrovica, J. X.: Secular trends in ocean tides: Observations and model results, *J. Geophys. Res.*, 116, C05 013, <https://doi.org/10.1029/2010JC006387>, 2011.
- Müller, M., Cherniawsky, J. Y., Foreman, M. G. G., and von Storch, J. S.: Seasonal variation of the M2 tide, *Ocean Dynamics*, 64, 159–177, <https://doi.org/10.1007/s10236-013-0679-0>, 2014.
- Pan, H., Zheng, Q., and Lv, X.: Temporal changes in the response of the nodal modulation of the M2 tide in the Gulf of Maine, *Continental Shelf Research*, 186, 13–20, <https://doi.org/10.1016/j.csr.2019.07.007>, 2019.

- Pawlowicz, R., Beardsley, B., and Lentz, S.: Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, *Computers and Geosciences*, 28, 929–937, [https://doi.org/10.1016/S0098-3004\(02\)00013-4](https://doi.org/10.1016/S0098-3004(02)00013-4), 2002.
- Pickering, M., N.C.Wells, K.J.Horsburgh, and J.A.M.Green: The impact of future sea-level rise on the European Shelf tides, *Continental Shelf Research*, 35, 1–15, <https://doi.org/10.1016/j.csr.2011.11.011>, 2012.
- Pickering, M. D., Horsburgh, K. J., Blundell, J. R., Hirschi, J. J.-M., Nicholls, R. J., Verlaan, M., and Wells, N.: The impact of future sea-level rise on the global tides, *Continental Shelf Research*, 142, 50–68, <https://doi.org/10.1016/j.csr.2017.02.004>, 2017.
- Pouvreau, N.: Trois cents ans de mesures marégraphiques en France: outils, méthodes et tendances des composantes du niveau de la mer au port de Brest, PhD thesis, University of La Rochelle, 2008.
- Pouvreau, N., Miguez, B. M., Simon, B., and Wöppelmann, G.: Évolution de l’onde semi-diurne M2 de la marée à Brest de 1846 à 2005, *C. R. Geoscience*, 338, 802–808, <https://doi.org/10.1016/j.crte.2006.07.003>, 2006.
- Pugh, D. and Woodworth, P.: *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*, Cambridge Univ. Press, Cambridge, U.K., 2014.
- Pugh, D. T. and Vassie, J. M.: Tide and surge propagation off-shore in the Dowsing region of the North Sea, *Deutsche Hydrographische Zeitschrift*, 29, 163–213, <https://doi.org/10.1007/BF02226659>, 1976.
- Ralston, D. K., Talke, S., Geyer, W. R., Al-Zubaidi, H. A. M., and Sommerfield, C. K.: Bigger tides, less flooding: Effects of dredging on barotropic dynamics in a highly modified estuary, *J. Geophys. Res. Oceans*, 124, 196–211, <https://doi.org/10.1029/2018JC014313>, 2019.
- Ray, R. D.: Secular changes of the M2 tide in the Gulf of Maine, *Continental Shelf Research*, 26, 422–427, <https://doi.org/10.1016/j.csr.2005.12.005>, 2006.
- Ray, R. D.: Secular changes in the solar semidiurnal tide of the western North Atlantic Ocean, *Geophys. Res. Lett.*, 36, L19601, <https://doi.org/10.1029/2009GL040217>, 2009.
- Ray, R. D. and Talke, S. A.: Nineteenth-century tides in the Gulf of Maine and implications for secular trends, *J. Geophys. Res. Oceans*, 124, 7046–7067, <https://doi.org/10.1029/2019JC015277>, 2019.
- Santamaría-Gómez, A., Gravelle, M., Dangendorf, S., Marcos, M., Spada, G., and Wöppelmann, G.: Uncertainty of the 20th century sea-level rise due to vertical land motion errors, *Earth and Planet. Sci. Lett.*, 473, 24–32, <https://doi.org/10.1016/j.epsl.2017.05.038>, 2017.
- Schindelegger, M., Green, J. A. M., Wilmes, S., and Haigh, I. D.: Can we model the effect of observed sea level rise on tides?, *J. Geophys. Res. Oceans*, 123, 4593–4609, <https://doi.org/10.1029/2018JC013959>, 2018.
- Simon, B.: *La marée océanique côtière*, Institut Océanographique Ed., Paris, France, https://iho.int/iho_pubs/CB/C-33/C-33_maree_simon_fr.pdf, 2007.
- Simon, B.: *Coastal Tides*, Institut Océanographique Ed., Paris, France, https://iho.int/iho_pubs/CB/C-33/C-33_maree_simon_en.pdf, 2013.
- Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Blancq, F. L., Lee, T., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K., and Wyszynski, P.: Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system, *Quart. Journ. Roy. Meteorol. Soc.*, 145, 2876–2908, <https://doi.org/10.1002/qj.3598>, 2019.
- Talke, S. A. and Jay, D. A.: Nineteenth Century North American and Pacific Tidal Data: Lost or Just Forgotten?, *Journal of Coastal Research*, 29, 118–127, <https://doi.org/10.2112/JCOASTRES-D-12-00181.1>, 2013.

- 665 Talke, S. A. and Jay, D. A.: Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future, Tech. rep., Civil and Environmental Engineering Faculty Publications and Presentations, 412., 2017.
- Talke, S. A. and Jay, D. A.: Changing Tides: The Role of Natural and Anthropogenic Factors, *Annual Review of Marine Science*, 12, 121–151, <https://doi.org/10.1146/annurev-marine-010419-010727>, 2020.
- Talke, S. A., Orton, P., and Jay, D. A.: Increasing storm tides in New York Harbor, 1844–2013, *Geophys. Res. Lett.*, 41, 3149–3155,
670 <https://doi.org/10.1002/2014GL059574>, 2014.
- Talke, S. A., Kemp, A., and Woodruff, J.: Relative sea level, tides, and extreme water levels in Boston (MA) from 1825 to 2018, *J. Geophys. Res. Oceans*, 123, 3895–3914, <https://doi.org/10.1029/2017JC013645>, 2018.
- Thompson, D. W. J. and Wallace, J. M.: The Arctic oscillation signature in wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, 25, 1297–1300, <https://doi.org/10.1029/98GL00950>, 1998.
- 675 Thompson, D. W. J. and Wallace, J. M.: Annular modes in the extratropical circulation. Part I: Month-to-month variability, *Journal of Climate*, 13, 1000–1016, [https://doi.org/10.1175/1520-0442\(2000\)013<1000:AMITEC>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2), 2000.
- Thompson, D. W. J., Wallace, J. M., and Hegerl, G. C.: Annular modes in the extratropical circulation. Part II: Trends, *Journal of Climate*, 13, 11 018–1036, [https://doi.org/10.1175/1520-0442\(2000\)013<1018:AMITEC>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2), 2000.
- Winterwerp, J. C. and Wang, Z. B.: Man-induced regime shifts in small estuaries—I: theory, *Ocean Dynamics*, 63, 1279–1292,
680 <https://doi.org/10.1007/s10236-013-0662-9>, 2013.
- Winterwerp, J. C., Wang, Z. B., van Braeckel, A., van Holland, G., and Kösters, F.: Man-induced regime shifts in small estuaries - II: a comparison of rivers, *Ocean Dynamics*, 63, 1293–1306, <https://doi.org/10.1007/s10236-013-0663-8>, 2013.
- Woodworth, P.: A survey of recent changes in the main components of the ocean tide, *Continental Shelf Research*, 30, 1680–1691, <https://doi.org/10.1016/j.csr.2010.07.002>, 2010.
- 685 Woodworth, P. L., Shaw, S. M., and Blackman, D. L.: Secular trends in mean tidal range around the British Isles and along the adjacent European coastline, *Geophys. J. Int.*, 104, 593–609, <https://doi.org/10.1111/j.1365-246X.1991.tb05704.x>, 1991.
- Woodworth, P. L., Pouvreau, N., and Wöppelmann, G.: The gyre-scale circulation of the North Atlantic and sea level at Brest, *Ocean Sci.*, 6, 185–190, <https://doi.org/10.5194/osd-6-2327-2009>, 2010.
- Wöppelmann, G. and Marcos, M.: Vertical land motion as a key to understanding sea level change and variability, *Rev. Geophys.*, 54, 64–92,
690 <https://doi.org/10.1002/2015RG000502>, 2016.
- Wöppelmann, G., Pouvreau, N., and Simon, B.: Brest sea level record: a time series construction back to the early eighteenth century, *Ocean Dynamics*, 56, 487–497, <https://doi.org/10.1007/s10236-005-0044-z>, 2006.

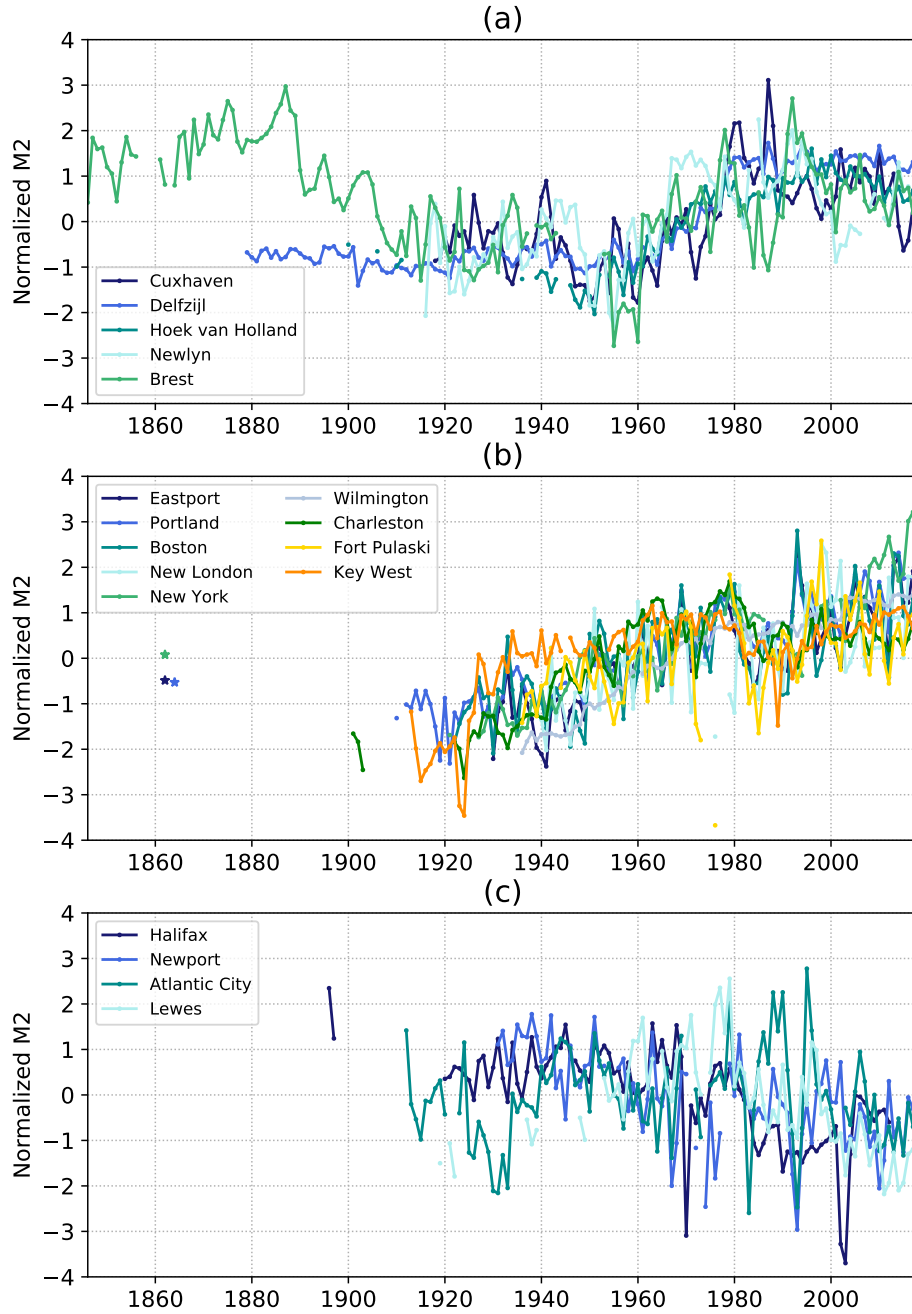


Figure 2. Normalized M_2 annual M_2 amplitude (a) in the North East Atlantic (~~Newlyn~~, ~~Brest~~, ~~Cuxhaven~~) (b) in the North West Atlantic, stations with positive trends (~~Portland~~, ~~Charleston~~, ~~Key West~~) (c) in the North West Atlantic, stations with negative or no trend (~~Halifax~~, ~~Atlantic City~~, ~~Lewes~~). The blue stars on in (b) corresponds to M_2 amplitude at Eastport and Portland from Ray and Talke (2019), and New York from Talke et al. (2014), after normalization (Eq. (1)).

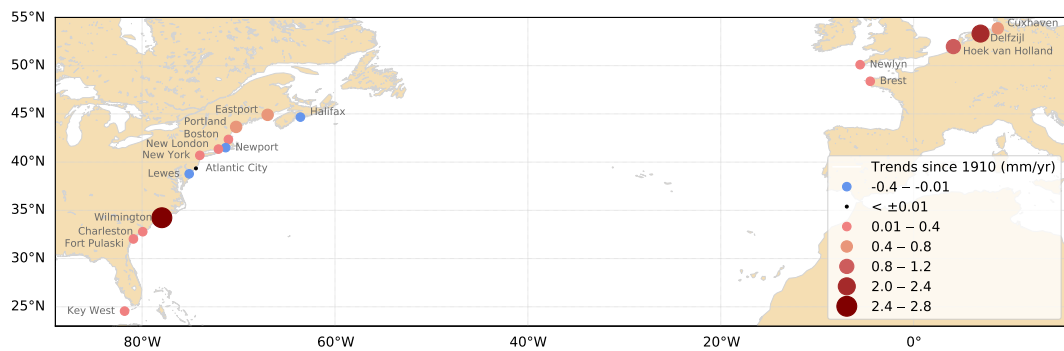


Figure 3. Estimated trends in M_2 amplitude over the period 1910-2018

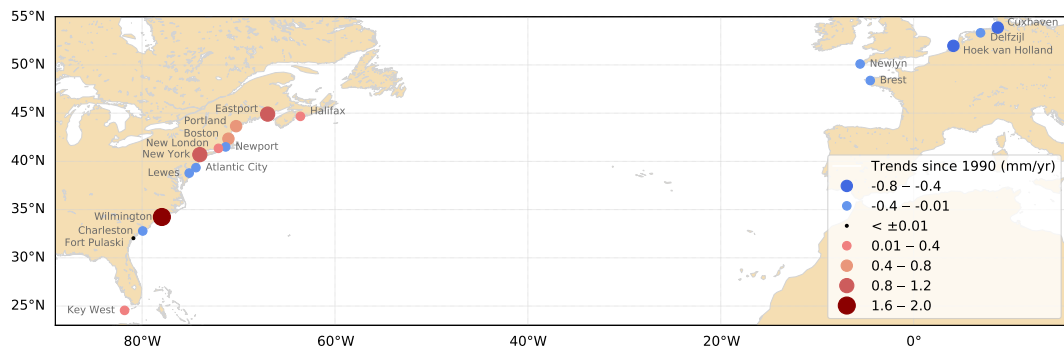


Figure 4. Estimated trends in M_2 amplitude over the period 1990-2018

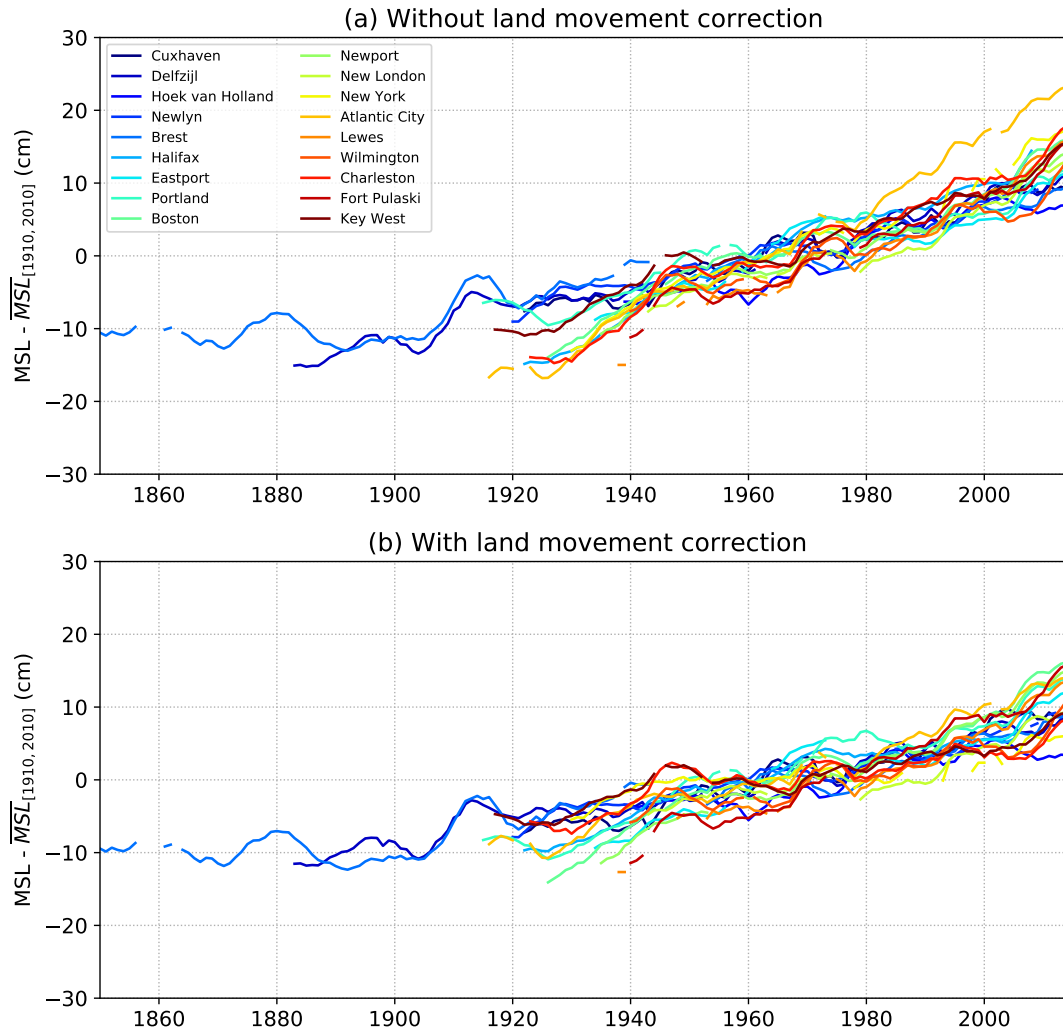


Figure 5. Annual ~~mean-sea-levels~~ Mean Sea Levels (MSL), after removing the average over the period 1910-2010 , (a) without land movement correction (b) with land movement correction. MSL are filtered over a 9-year time windows. (see Table 1, column 5)

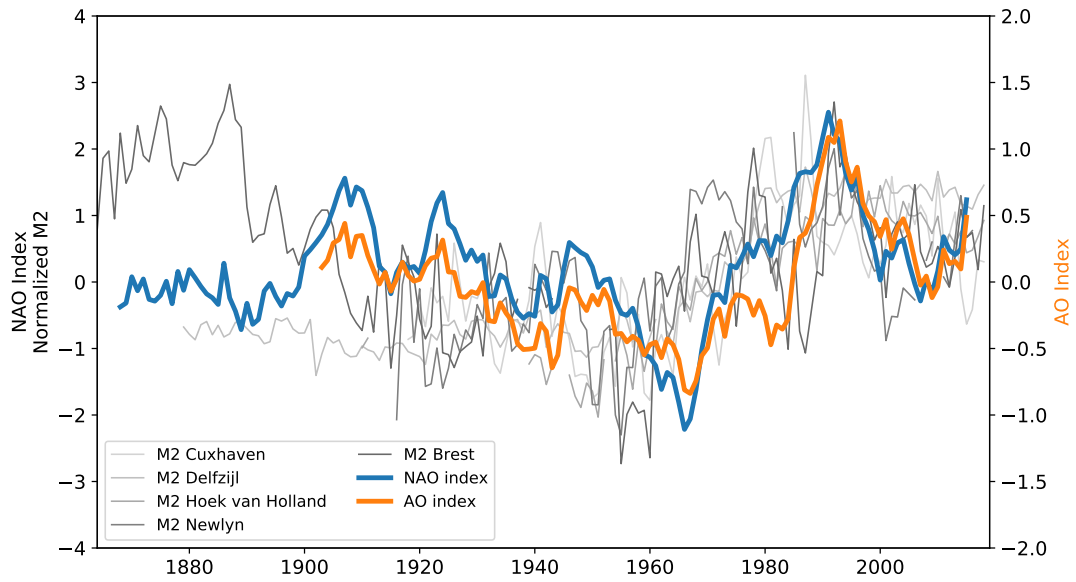


Figure 6. NAO and AO indices. Blue bars correspond to annual values of NAO index. Blue and green lines correspond to low frequency variations of NAO and AO, obtained with a 9-year median filter. Low frequency winter NAO and AO indices, obtained with a 9-year mean filter. Normalized annual M_2 amplitude in the North East Atlantic (from Figure 2 (a)) are also plotted in grey.

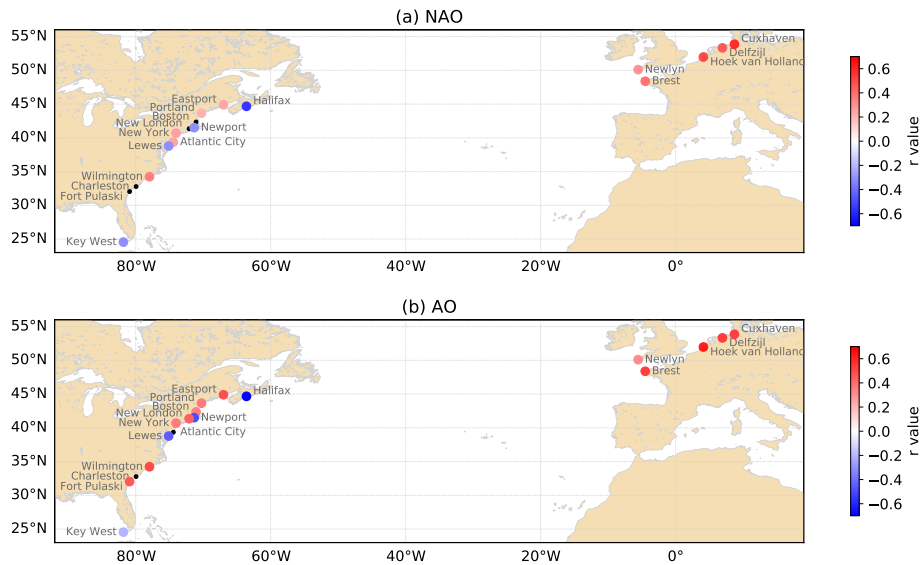


Figure 7. Correlation (r -value) since 1910 between M_2 and (a) North Atlantic Oscillation and (b) Arctic Oscillation. Black dots are stations with no significant correlation. M_2 , NAO and AO are filtered on the same time window (9 years).

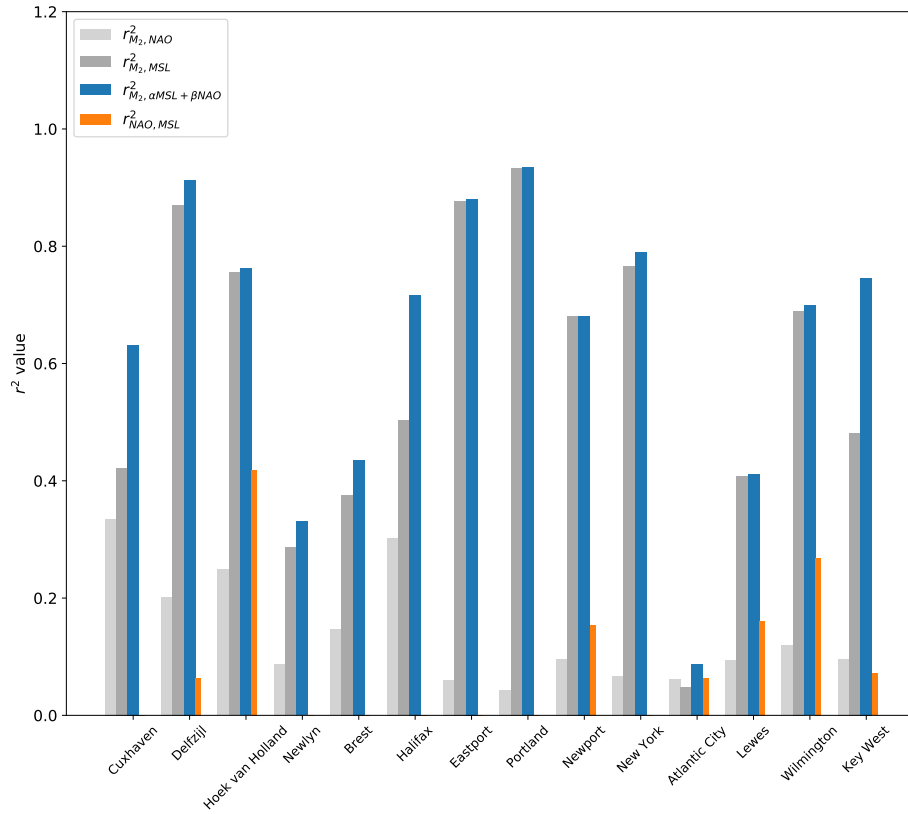


Figure 8. r^2 -value since 1910 between M_2 and NAO, M_2 and MSL, M_2 and fitted model $\alpha MSL + \beta NAO$ (model 2), NAO and MSL. M_2 , NAO and MSL are filtered on the same time window (9 years). Note that there is no orange bar for NAO-MSL correlation when correlation is not significant ($p > 0.05$).

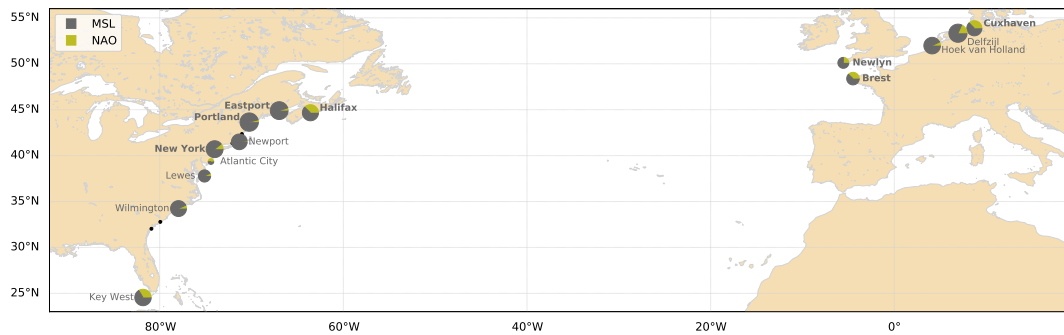


Figure 9. Relative contribution of α compared to β in the fitted model $\alpha MSL + \beta NAO$. Black dots are stations with no significant M_2 -NAO correlation. The size of the pie is proportional to the correlation between M_2 and the fitted model. Stations with no MSL-NAO correlations are labelled in bold.

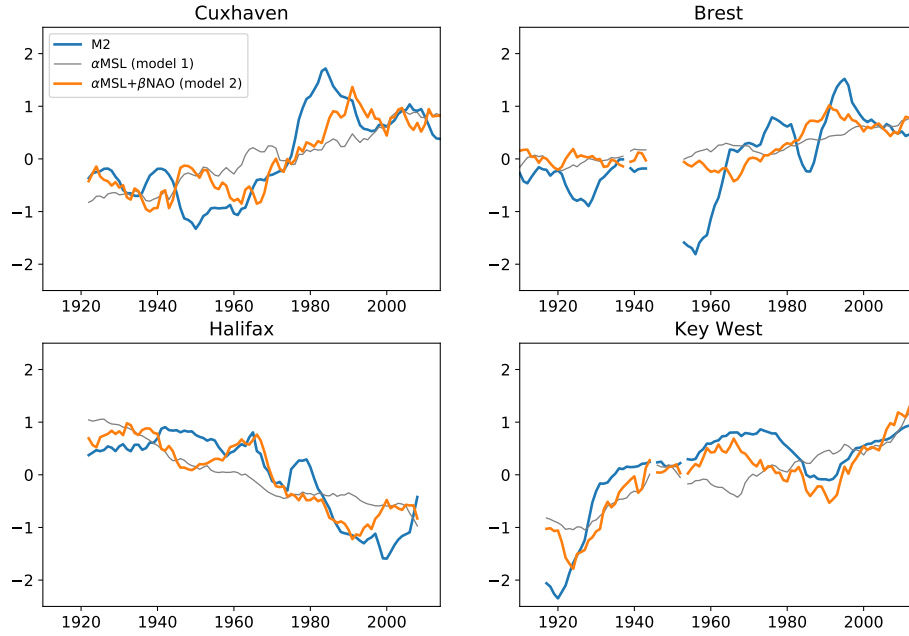


Figure 10. Variations since 1910 of M_2 , αMSL (model 1), $\alpha\text{MSL} + \beta\text{NAO}$ (model 2). M_2 , NAO and MSL are filtered on the same time window (9 years).

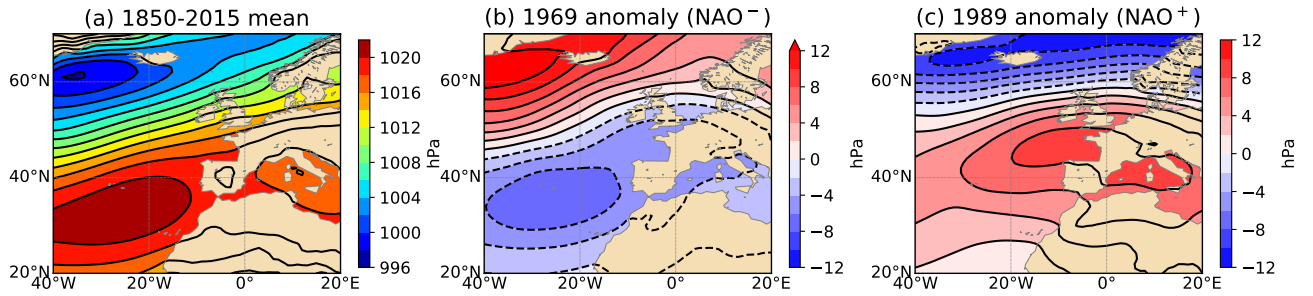


Figure 11. Winter sea-level pressure over the North East Atlantic (a) average over 1850-200215 (b) anomaly in 1969 (NAO^-) (c) anomaly in 1989 (NAO^+)

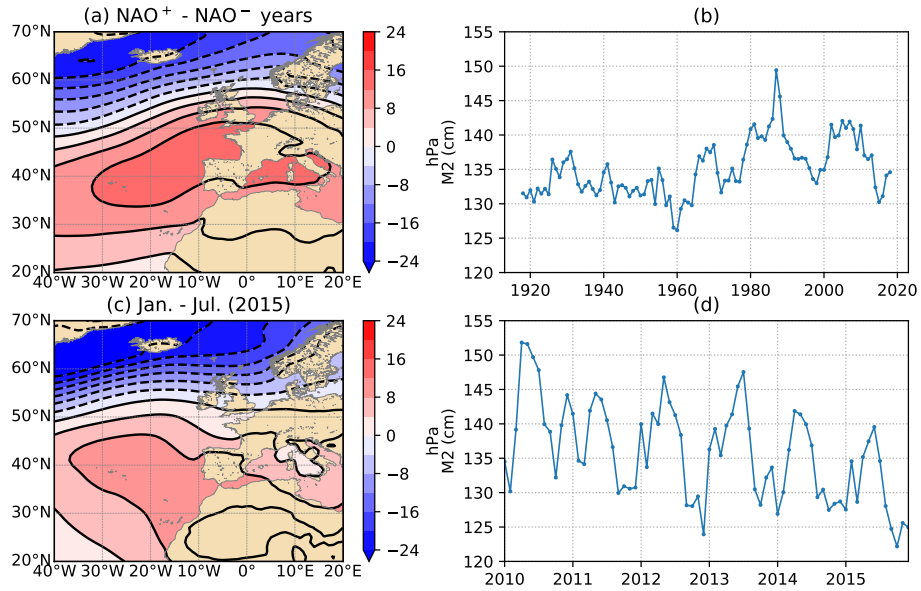


Figure 12. At decadal time scale: (a) Difference of winter sea-level pressure between 1989 (NAO⁺) and 1969 (NAO⁻) (b) Annual M_2 amplitude at Cuxhaven from 1918 to 2018. A seasonal time scale: (c) Difference of monthly sea-level pressure between January and July 2015 (d) Monthly M_2 amplitude at Cuxhaven from January 2010 to December 2015.

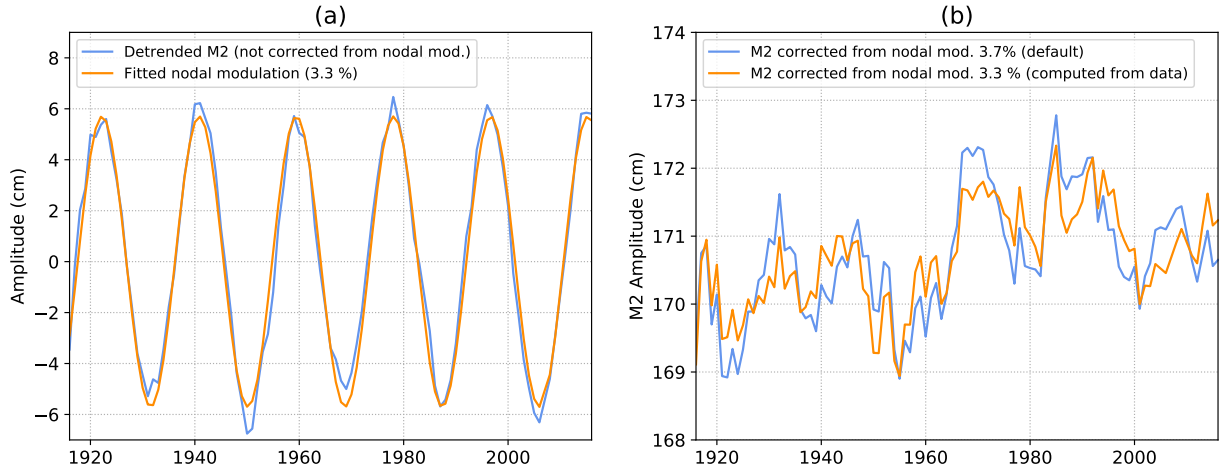


Figure A1. (a) Estimation of M_2 nodal modulation the nodal modulation of M_2 amplitude (mean removed) at Newlyn (b) Impact of M_2 on M_2 amplitude of the nodal modulation correction at Newlyn

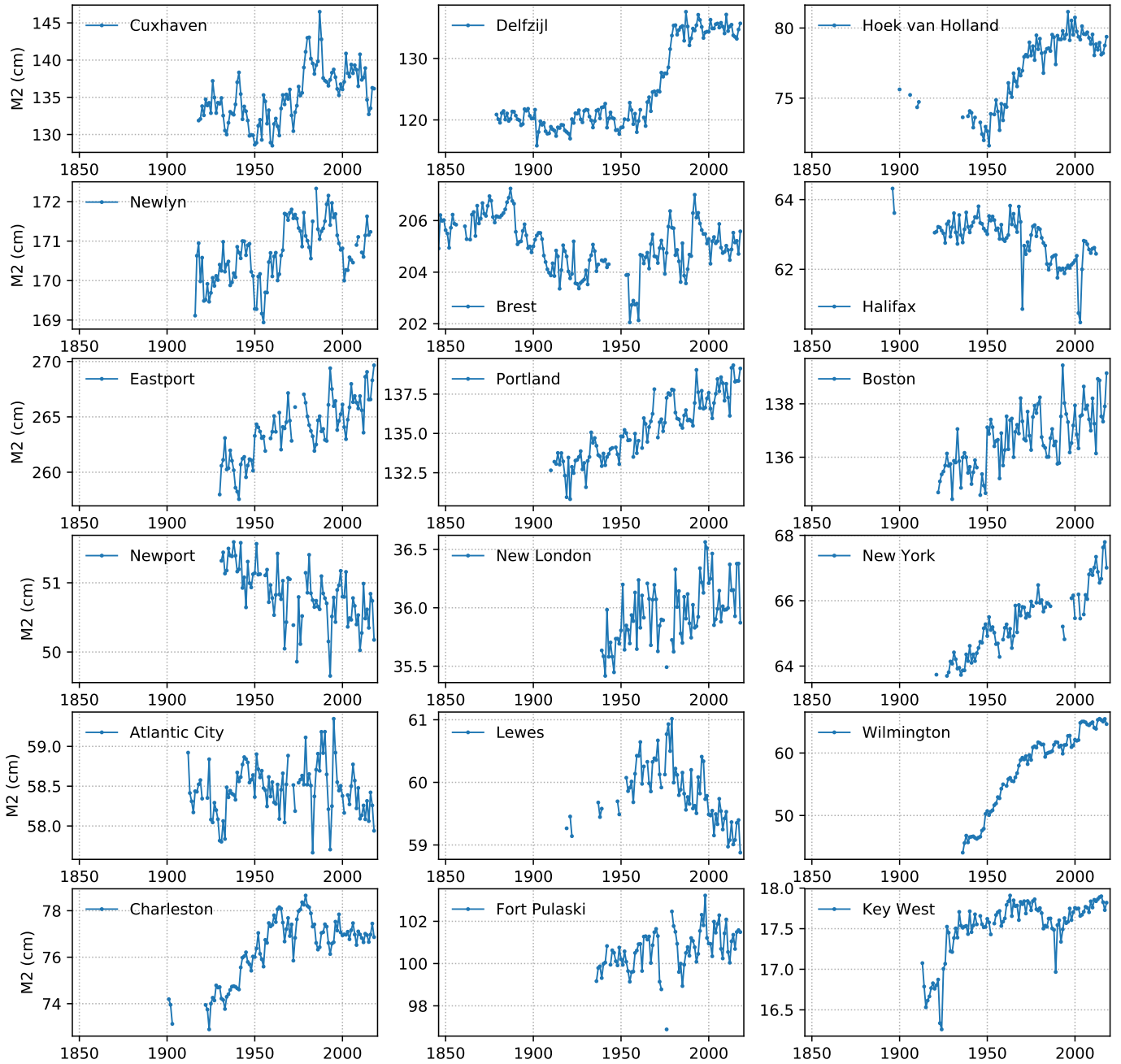


Figure B1. Annual M_2 amplitude at the 18 selected tide gauges