Response to Referee Comment #1 (Anonymous)

We thank the reviewer for his careful reading of the paper. The reviewer remarks led to important changes in the manuscript. We went further in the analysis, we have now new results, and the manuscript has been substantially rewritten.

In the following, the reviewer comments are in bold, our replies are in normal font.

In this paper, nine very long (>80-year) tide gauge records along North Atlantic coasts are analyzed for secular changes in the M2 amplitude. The series are compared both among each other and with climate mode indices in an attempt to relate the observed amplitude changes to large-scale forcing mechanisms. Unfortunately, the paper is of limited scope and the methods are not innovative.
We agree with the reviewer that the methods may not be innovative, but they are robust, and our tidal analyses are rigorously undertaken and as accurate as one can expect from the state-of-the-art knowledge.

The arguments put forth to link the observed M2 changes to the North Atlantic Oscillations (NAO) are fallacious (see below) and invalidate exactly that part of the paper that is thought to break fresh ground compared to similar analyses in the past (e.g., Mueller 2011, GRL).
We bring now quantitative insights on the possible influence of NAO, which was already mentioned by Müller (2011) on the basis of qualitative criteria.

These shortcomings are not easily redressed in a revision, and I therefore recommend the manuscript to be rejected. Overall, the study offers too little new insight. It merely highlights similarities without investigating the underlying processes.
We went further in the data exploration to link the M2 variations with the NAO. We have now some new insight from the statistical analysis. We fitted a series of linear regression models, either only MSL-dependent (model 1) or MSL and NAO-dependent (model 2) on M2 variations (see below for the details). We found that M2 variations are correlated at first order with MSL, and at second order with NAO, at many stations. Taking into account the NAO in the model (model 2) systematically increases the correlations (compared to model 1). We estimated the part of the contribution of the NAO compared to MSL in the M2 variations. We found that this contribution is at some stations negligible (<10%), but at others significant, e.g. more than 30% at Cuxhaven or Halifax. These stations are mainly located in the northern part of the North Atlantic. The correlation with the NAO is positive on the northeast side, but negative on the northwest side (except in the Gulf of Maine). This suggests a basin scale coherence in the data.

Major issues:
[-] The authors' explanation of the pronounced M2 increase over 1960–1990 at the three European stations (∼3 cm at Brest and Newlyn, ∼10 cm at Cuxhaven) in terms of typical NAO sea-level pressure patterns is flawed. The response of sea level (or water column thickness) to changing pressure loading on time scales longer than a few weeks is static isostatic (IB), creating a sea-level difference of about 6–10 cm at the location of the tide gauges, according to the authors' plots (Figures 8 and 9). These changes in water depth are simply too small to cause the observed M2 amplitude trends. Typically, sea-level changes alter the propagation characteristics

of tides in shallow water such that one can expect perturbations in the M2 amplitude of 1–5% relative to the imposed water depth change, see the modeling results by Schindelegger et al. (2018). Cuxhaven may be an exception of that rule, although a 6-cm increase in sea level from atmospheric pressure will engender less than 2 cm changes in the M2 amplitude (Figure 8 of Schindelegger et al.).

Schindelegger et al. (2018) clearly underestimate the M2 response to MSL rise in terms of magnitude (see their Figure 7). Simulations show that the sign of the M2 trend is correctly reproduced at 80% of the tide gauges, but trend values tend to differ by a factor 3 to 5. Moreover, the response to a 0.5 m MSL rise is opposite between Cuxhaven and Brest (see Figure 6), whereas the observed changes are of the same sign (positive) at these two stations (their Figure 6, red dots). In terms of magnitude, simulations show M2 changes of around 1 cm (absolute value) at Brest and Newlyn, and 3 cm at Cuxhaven for a 0.5 m MSL rise (see Figure 6), whereas observed M2 changes for a smaller MSL rise (0.2 m MSL rise over the XXth) are as large as 5 cm , 3 cm and 15 cm at Brest, Newlyn and Cuxhaven, respectively (results from our study). Schindelegger et al. (2018) conclude that "magnitudes of observed and modeled M2 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 (as in Schindelegger et al. (2018)), but results in terms of values 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 model and the observations also strongly suggest that mean sea level rise is not the only process that may explain M2 changes – other large-scale processes, in addition to local processes, may combine and interact together.

We conducted further investigations to test if the magnitude of sea-level pressure changes induced by large-scale atmospheric circulation (Figure 9, few tens of hPa) can generate the observed decadal-scale M2 changes (few cm). Note that we now express the Figure 9 in terms of hPa (and not cm). It is directly the difference of winter sea-level pressure between a NAO+ year (1989) and NAO- year (1969). Note also that M2 changes due to large-scale atmospheric circulation are only a small part of the total observed changes (few cm), the changes being also due to MSL rise (see the statistical analysis).

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 in Huess and Andersen (2001), except that we are at a larger time scale (decadal instead of seasonal). Huess and Andersen (2001) explains partly M2 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. Results show that the seasonal modulation is better captured when the model is forced with both tides and meteorological fields (Plate 2, top right, amplitude higher that 10 cm in the German Bight) rather than with tides only (Plate 2, top left, amplitude lower that 5 cm in the German Bight). It is important to underline that the model is barotropic, and that there is no effect of stratification, which may also play a role in M2 changes (see 3.3.6 in the review of Haigh et al, 2019).

At seasonal scale (instead of decadal scale, in the present paper), we computed monthly (instead of yearly) M2 variations at Cuxhaven over 5 years (2010-2015). Results show a seasonal cycle with a range of around 15 cm, maximum in summer, and minimum in January (which is consistent with Huess and Andersen (2001)). Similarly to Figure 9 in our paper (now in hPa), we computed the difference of monthly sea-level pressure between January and July (sea-level pressure data come from NOAA 20th-Century Reanalysis, Compo et al. 2011). We obtain values very close to the ones in Figure 9 (few tens of hPa). This shows that the order of magnitude of sea-level pressure changes (few tens of hPa) is consistent with M2 observed changes at Cuxhaven (few cm). The assumption is not strictly proven, but we provide reasonable new insights worth to be brought to the attention of the community for further investigations. As mentioned in the paper, dedicated simulations should be conducted to go further, and confirm or discard this hypothesis.

The authors circumvent the problem by assuming higher sea-level changes in areas distant to the gauges (-20 cm near Island) and picking a 10% sensitivity of M2 amplitudes to water depths from literature – an inordinate value that only holds in very shallow settings (e.g., estuaries) and not across entire shelf regions.
As all the tide gauges are in coastal areas, and potentially in estuaries or very shallow waters (e.g. Cuxhaven is located in the Elbe estuary) , we focused on values nearshore rather than offshore. Idier et al. (2017) show that depending on the location, the changes can account for +/−15% of regional SLR, whereas Schindelegger et al. (2017) reports relative magnitude of 1-5 % per century in the North Atlantic. The value of 10% is an order of magnitude of the changes in shallow waters. As mentioned previously, Schindelegger et al. (2018) correctly simulate the sign of M2 trends at 36 of 45 stations, but in terms of magnitude, there are strong discrepancies between the model and the observations.

Following the reviewer suggestion, we have substantially rewritten this part, and introduced an analogy with the seasonal variation (see above).

Moreover, Figure 8 displays higher atmospheric pressures around the European mainland in 1989, implying that sea level actually dropped relative to 1969, opposite to what is shown in Figure 9.
Yes, we thank the reviewer to point out this error, there was an error of sign. Figure 8 shows the difference between years 1969 and 1989 (and not the contrary). However, we express now this differences in terms of hPa, and the figure has been updated (hPa instead cm for the unit).

So that's an inconsistency on its own, but more alarmingly for the authors' theory, numerical modeling (see references) strongly suggests that an increase of M2 in the German Bight, as observed at Cuxhaven, actually requires local sea level to rise, not to fall.
Yes, but the same simulations also suggest that an increase of M2 in the Western Channel, as observed at Brest, actually requires sea level to fall, not to rise. The underlying problem is that these simulations (e.g. Schindelegger et al., 2018; Pickering et al. 2017) show opposite signs between Brest and Cuxhaven, whereas observations show the same sign (red dots on Figure 6 of Schindelegger et al. (2018) or Figure 3 (a) of our paper).

[-] A key argument is that the low-frequency winter NAO index (Figure 7) is similar to the evolution of the M2 amplitude at the three European stations. Such an important point in the paper should be substantiated by an appropriate plot (in which annual M2 changes would be filtered using the same 9-year running median as the NAO index).
Yes, we agree with the reviewer. We propose to add a new figure with M2 variations (filtered in the same way than NAO), model 1, and model 2 (see below) at the stations where the correlation with model 2 is significant ($p<0.05$ and r-value>0.3) and the NAO contribution significant ($\beta/\alpha>0.25$, see

its definition below). This new figure shows that the model 2 better captures the M2 variations than model 1.

More importantly, the mentioned similarity is never established in a quantitative sense, e.g., by tabulating correlation measures and their statistical significance considering effective degrees of freedom. In fact, the Brest time series in Figure 3a seems to have rather little in common with the NAO time series as it has a dip in the 1980s (when NAO steadily increases) and features an all-time high in the late 19th century (when NAO just erratically switches sign). For Newlyn and Cuxhaven, I expect the correlations to be higher, although the timing of individual peaks might be different. Such phase lags and leads are not easily explained in terms of physics; certainly not within the framework proposed here, because both sea level and subsequently tides would adjust instantaneously to NAO-related atmospheric pressure loading.
We agree with the reviewer, and to establish the similarity in a more quantitative sense, we conducted a statistical analysis.

1) We computed the correlation between normalized M2 variations and climate indices (NAO and AO). To be consistent, we filtered out M2 variations on the same time window as NAO and AO (9 years). We computed the correlation since 1910, to have similar periods for all the stations. We considered that the correlation was significant only if the p-value was lower than 0.05 (95% significance level). The results are the following: for NAO only, 10 stations out of 12 show significant correlation. We found the strongest positive r-value in the North East Atlantic (Cuxhaven, Brest, Newlyn), with a maximum of 0.58 at Cuxhaven. This confirms the possible causal relationship between M2 variations and NAO, as suggested in the paper. We also found a strong anti-correlation with Halifax (-0.55). For AO, we found similar, but generally overall larger, r-values. This is not surprising as these two indices are highly correlated. We propose to add in the paper a figure showing the r-value at all the stations with (a) NAO and (b) AO.

Note that at Brest the data records starts in 1846. The correlation with NAO is significant from 1910, but not from 1864 (NAO index used in this study starts only in 1864). This can be explained by the M2 larger amplitude over all the XIXth century, which decreases between 1890 and 1910 (Figure 3a). This inconsistency was already noticed by the reviewer. However, the construction of dykes that partially closed the harbor of Brest since the end of the XIXth century may have altered the tide. To go further, the potential role of these successive constructions needs to be investigated (https://en.wikipedia.org/wiki/Brest_Arsenal). Cartwight (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 local and large-scale changes occur at the same time.

In the following, M2 variations, MSL and NAO are filtered over 9-year time windows and normalized. MSL are now corrected for land movement (estimations from SONEL website), which led to more consistent MSL trends at the basin scale.

2) We computed the r-value between M2 variations and two linear regression models. First, we fitted M2 variations with MSL variations only (model 1). We then computed the residual (M2 variations – model 1), and fitted this residual with a NAO linear model. The objective is to estimate the relative contribution of MSL and NAO in M2 variability. Models 1 and 2 may be expressed as:

Model 1 = αMSL
Model 2 = αMSL+βNAO

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 0.4 at 5 stations; note that there is no NAO-MSL corrrelation at the stations in the north (Halifax, Brest, Cuxhaven, Newlyn), where we found a significant NAO contribution compared to MSL - see below).
The three main results of this analysis are the following: the first result is that at first order, M2 varies with mean sea level (strong r-value for model 1). The second result is that the introduction of NAO in the model (model 2) allows to systematically increase the correlation (stronger r-value for model 2 than for model 1). This confirms that NAO-related mechanisms may explain a part of the variability of M2. At some stations, this increase is quite large. For example, at Cuxhaven, the r-value is 0.65 for model 1, but reaches 0.85 for model 2. The third result is that we can estimate at each station the relative NAO contribution (compared to MSL) in M2 variability. Indeed, as in model 2 MSL and NAO are normalized, the ratio β/α represents roughly this relative NAO contribution. We found a significant NAO contributions at some stations (e.g. more than 30% at Halifax), whereas negligible at others (e.g. 5% at Eastport). Values suggest that the northern part of North Atlantic is more sensitive to NAO, with quite similar values. This suggests a possible basin scale coherence, with correlation on the northeast side, and anti-correlation on the northwest side. We propose to add in the paper a table including the r-value for models 1 and 2 and the ratio β/α .

[-] The data basis on the European Shelf (three stations) is very shaky. It would be desirable to make the analysis more robust by adding results from tide gauges that are somewhat shorter but still provide good coverage of the period with distinct variability in NAO (1960 onwards).
We agree with the reviewer that it would be interesting to have more tide gauges. However, this would lead to add short records, whereas the present paper focuses on long-term records starting no later than 1930 and with at least 80 years with data. Moreover, the study would then be closer to Müller (2011), who selected tide gauges with at least 35 years of data prior to the year 1980, leading to 17 stations. Finally, shorter series are affected by stronger correlations between the NAO and the MSL (as they increase since 1960), which is problematic for the statistical analysis, when fitting model 2 to distinguish the influence of the MSL from that of the NAO. From 1910, only 5 stations out of 12 show a significant correlation between MSL and NAO (on average, r=0.28), whereas from 1960, this figure jumps to 9 stations, with higher r-value (on average, r=0.40).

However, to confirm the results on the European Shelf, we led a similar analysis on Calais and Dunkerque stations, located in the North of France (North Sea). Calais starts in 1941, with only two years 1941-1942, and then a gap until 1965, and data from 1965 up to now. Dunkerque starts in 1956. The results confirm that the variations at these two stations are similar to the variations at the 3 other stations in the North East Atlantic (Newlyn, Brest, Cuxhaven, Figure 3(a)). M2 increases from 1960 to 1990, and then becomes more steady since 1990. Similarly to the three other stations in North East Atlantic, the trends are decreasing when they are computed only since 1990. However, the main difficulty with these short time series (since 1960) is that the correlation between NAO and MSL is significant (see above). For example, at Dunkerque, the correlation coefficient is 0.53.

Finally, note that following reviewer #2 suggestion, we select now time records starting before 1930 (instead of 1920), which led to add 3 new stations (New York, Boston, Eastport).

[-] The Introduction leaves a lot to be desired. It is incoherent, lacks any quantification as to the size of observed tidal changes and does not tell the reader why he/she should bother. A very good example of clarifying the relevance of this subject matter up front is Mawdsley et al. (2015, https://doi.org/10.1002/2014EF000282).
We thank the reviewer for the reference. Following the reviewer suggestion, the introduction has been substantially rewritten.

Minor comments (most of these issues are indications of the authors' unsteadiness regarding the physics of tides):
[-] The Introduction's first sentence is wrong. Tides have been changing also prior to 19th century, e.g., due to Earth's continental and glaciation cycle.
We agree that the tides have been changing also prior to 19th century (Haigh et al., 2020), this first sentence may be read in the context of the paper, which concerns the period "from 1846 to 2018". We have rephrased to be more precise, following the Editor suggestion: "Tides have been changing due to non-astronomical factors since the XIXth century (Haigh et al., 2019; Talke and Jay, 2020)."

[-] The main tidal constituents in the North Sea are presently not in a state of resonance (as argued on lines 172 and 219). They are rather described as Kelvin waves, dampened as they propagate from the Northwest through the basin in cyclonic fashion.
We mentioned line 172 of the submitted paper, that amplification could be due to resonance effects and/or propagation in shallow waters. We agree with the reviewer, that the amplification of M2 in Cuxhaven is probably due to propagation in shallow waters rather than resonance (we corrected this point). Cuxhaven is located in the German Bight, shallow depths and shape of the coastline could induce some amplification. Variations in M2 at Cuxhaven are therefore very 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 (Wintewerp & Wang, 2013; Wintewerp et al., 2013) (see suggestion from reviewer #2). We have rephrased, mentioning a possible amplification due to resonance effects (e.g. Portland) and/or propagation in shallow waters (e.g. Cuxhaven), in addition to local effects.

[-] Lines 250–252: First, stratification will not only change in response to heat fluxes, but also due to the advection of water masses, evaporation, salt dilution, etc. Second, in a discussion of stratification effects on "tides", one must use very precise language, in particular distinguish between barotropic, baroclinic, and surface (barotropic + baroclinic) tides. Third, the process identified by Kang et al. (2002) as cause for tidal seasonality in the Yellow/East China Sea is mixing strength (changes of vertical eddy viscosity) and not barotropic-to-baroclinic energy conversion.
We agree with the reviewer that our description of the links between climate and tidal indices was somewhat sketchy, and this paragraph has been partially rewritten. 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 later effect acts on the stratification which itself 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 and this effect has not lead, so far, to much attention in the North Atlantic. More important is the second effect: the impact of the stratification which acts on the eddy viscosity profile by modifying currents profile and bottom drag over continental shelf and ultimately modifying the M2 surface expression (Kang et al, 2002; Müller, 2012; Katavouta et al., 2016).

[-] Lines 231–234: The simulations of Pickering et al. (2017) show exactly the opposite of what is described here (that is, their Figure 1a highlights an M2 increase in the German Bight, not a decrease).
Yes, we thank the reviewer for this remark, it has been corrected. However, what we wanted to point out here (see the following sentence), is that Pickering et al. (2017) showed that the effect of mean sea level rise is opposite between the western part of English Channel and German Bight (decrease/increase), which is not consistent with observations, as M2 varies the same way at the stations located in these areas (Figure 3 (a)). This supports the idea that MSL rise is not sufficient to explain alone the secular changes in tide (and/or that simulations have strong uncertainties).

[-] I understand the pragmatic approach of normalizing M2 changes to show results from different stations in one plot, but it would still make sense to include some absolute numbers (e.g., by using text or secondary Y axes) to facilitate quantitative comparisons among stations and allow for a meaningful interpretation of results derived later on.
We understand the reviewer concern, but it is quite difficult to add a secondary Y axis and keep a readable figure. To follow the suggestion, we propose to add in the Appendix a new figure displaying the variations of M2 (without normalizing) at all the stations.

[-] Annual tidal harmonics are computed from data spanning full years, but the discussion of atmospheric pressure changes only focuses on snapshots from winter months – another inconsistency in the analysis. Surely, if annual averages of atmospheric pressure fields are considered, the magnitude of the static sea-level response would decrease even further.
We agree with the reviewer that we used only winter AO and NAO indices, which show more variability than annual indices. We conducted a similar analysis with annual indices. Preliminary results show consistent results for the correlation with AO: positive correlation on the east side and positive and negative correlation on the west side, depending on the stations. However, we noticed that 4 stations show no significant correlation using annual values, against only 2 using winter values. For the correlation with NAO, the number of stations without significant correlation jumps from 2 to 7. As underlined by the reviewer, with annual rather than monthly indices, the difference of pressure fields will decrease (being roughly divided by 3 following our results), and as a consequence, the magnitude of the sea-level response will also decrease. This point has been added in the limitations of the paper.