Seasonal Shift in Storm Surges at Brest Revealed by Extreme Value Analysis

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Key Points:

- Extreme storm surge events occurred three weeks earlier in Brest in the winter 2000 than in the 1950s
- Shift of winter storm surge timing was calculated consistently with two statistical methods
- Analysis of additional stations in Europe suggests a large-scale process

Supporting Information:

Supporting Information may be found in the online version of this article.

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Seasonal Shift in Storm Surges at Brest Revealed by Extreme Value Analysis

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Abstract Global warming changes the Earth's climate in different ways, in particular it influences extreme weather events like storms. Strong storms cause large surges and thus have a signature in the sea level record. While previous studies focused on long-term changes of storm surge amplitude or frequency, changes in the timing of extreme surge events have not been investigated so far. We employed the more than 150 yr long tide gauge record of Brest (France) and found a distinct shift of storm surge timing between the years 1950 and 2000. This caused extreme events to happen about three weeks earlier during the year. We developed for this study two different methods based on statistical extreme value analysis; both methods show this shift of the seasons consistently. Furthermore, by analyzing eight additional stations, we found evidence that this timing shift happened similarly over a large part of the European Atlantic coast. Therefore, we speculate that our measured shift is part of a large-scale climate process.

Plain Language Summary Climate change leads to an increase of the sea level all over the world. This means not only that the average sea level rises, but also that extreme sea levels become higher, which presents a major threat for coastal communities. To prepare for this growing natural hazard, it is important to understand how extreme sea levels evolve in a warming climate. One of the best places to study this is the harbor of Brest, France, which has one of the longest sea level records in the world (over 150 yr). From this time series, we extracted the surge, which is the part of the sea level that is created by large-scale atmospheric forcing, like storms. We used two statistical methods to analyze the extreme surge levels in Brest, and we found that between 1950 and 2000, the season of large surge levels shifted forward. In 2000, extreme storm surge events happened three weeks earlier than 50 yr before. We then analyzed sea level records of other stations and found the same shift over large parts of the European Atlantic coast. So we conclude that this shift of the extreme surge season might be the signature of a large-scale climate process.

1. Introduction

Climate is changing due to global warming and many of the observed changes since the 1950s are unprecedented over many centuries to many thousands of years (IPCC, 2021). Since the end of the 20th century, the frequency and intensity of the strongest storms have been increasing in the North Atlantic (IPCC, 2013). Damage resulting from storm surges, sea level rise, and coastal flooding presents a major risk for Europe (IPCC, 2014). It is thus essential to investigate how extreme sea levels and storm surges change in a warming climate, in the perspective of predicting them and adapting coastal areas accordingly to future changes.

Extreme high sea levels are the joint effect of mean sea level (MSL), tide, and storm surges. Storm surges are generated during extreme weather events such as extra-tropical storms or cyclones, and result from strong, large-scale atmospheric forcing (e.g., Dangendorf et al., 2016). The European coasts are regularly impacted by mid-latitude extra-tropical storms, which cause large surges, i.e., greater than 1 m. This may lead to huge economic losses and sometimes loss of human life. For example, the storm Xynthia hit the French coast severely on February 27 and 28, 2010, causing a large surge of 1.53 m in the harbor of La Rochelle (see location on Figure 1). This was the highest surge ever observed since the installation of the tide gauge in 1997; its return period was estimated to be greater than 100 yr (Pineau-Guillou et al., 2012). This exceptional storm event caused a major coastal flooding (Bertin et al., 2014). Forty-seven people were killed, around 10,000 people had to be evacuated, and the losses were estimated to more than 2.5 billion Euros (Genovese & Przyluski, 2013).

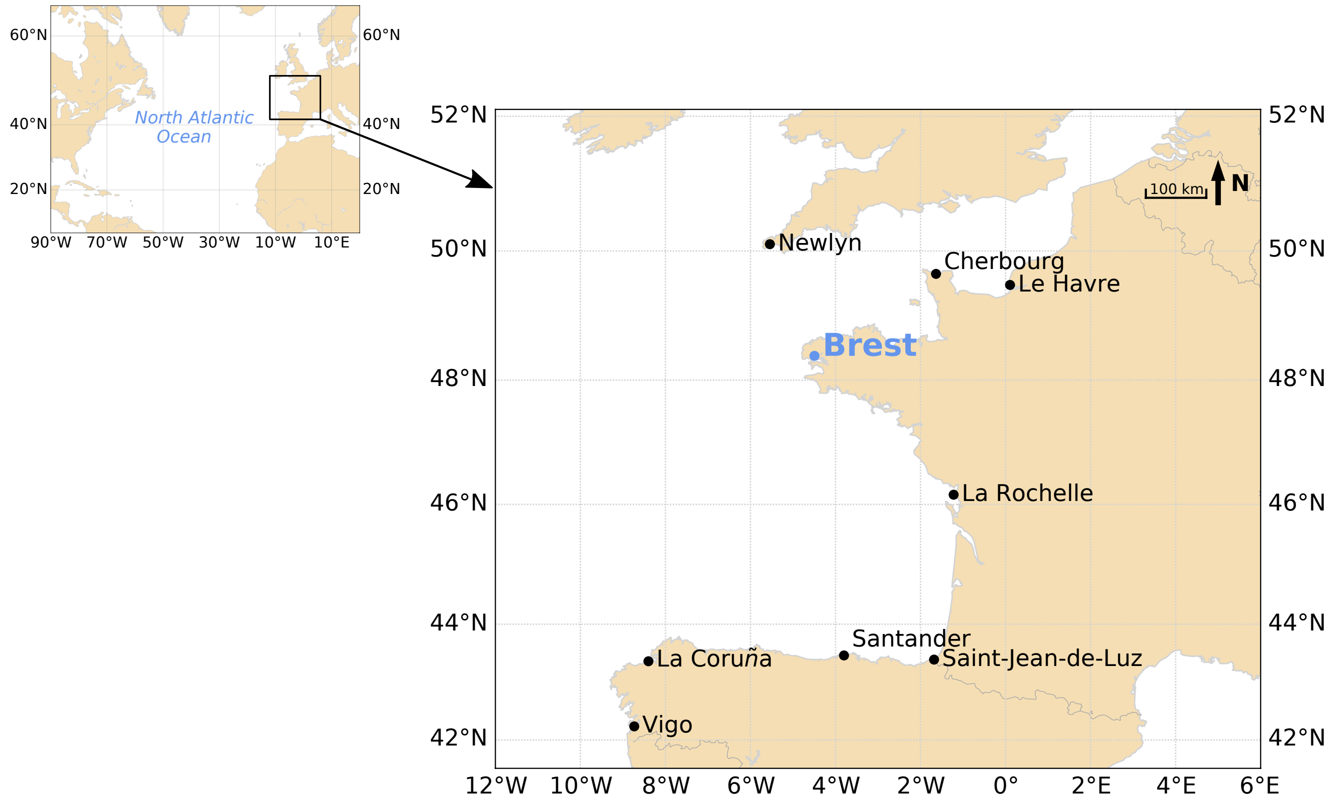

Figure 1. Location of the Brest tide gauge and the other stations used in our study.

Different studies investigated changes in storm surges over the last decades, based on analyses of tide gauges (Marcos & Woodworth, 2017), satellite altimeters (Ji et al., 2019), or numerical hindcasts (Fernández-Montblanc et al., 2020). Existing studies have been exploring (1) their variability and (2) their long-term trends (decadal to centennial).

1. Storm surges show strong interannual to multidecadal variability. It has been demonstrated that this variability is linked with large-scale atmospheric climate indices. Menéndez and Woodworth (2010) analyzed 258 tide gauges worldwide and showed strong correlations between storm surges and climate indices such as the Arctic Oscillation and the North Atlantic Oscillation (NAO; Hurrell & Deser, 2009). For the North Atlantic, Marcos and Woodworth (2017) reported positive correlations between these climate patterns and storm surges above 50°N (e.g., the English Channel, the North Sea), and negative correlations below 50°N (e.g., the Atlantic coasts of Spain and the United States). Thus, much of the variability in extremes can be accounted for by climate indices (Wahl & Chambers, 2016). For New York, Talke et al. (2014) showed that half of the long-term variance of the storm tides (i.e., storm surge and tide) is linked with NAO.
2. Concerning long-term trends, whereas extreme sea levels have been increasing globally, mainly due to the MSL rise (Marcos & Woodworth, 2017; Menéndez & Woodworth, 2010; Woodworth & Menéndez, 2015), there is no clear long-term trend in storm surge amplitudes. Mawdsley and Haigh (2016) analyzed 220 tide gauges worldwide and found that only 13% had a significant trend, with half of them positive and half of them negative. The study by Marcos and Woodworth (2017) for the North Atlantic did not find evidence for an overall increased storm activity, neither along the European nor the North American coast. By contrast, other studies reported some significant trends in storm surges: Fernández-Montblanc et al. (2020) reported a moderate increase (<5 mm yr^{-1}) in extreme storm surge in Southern Europe (<50°N) and a decrease (>-5 mm yr^{-1}) in Northern Europe, based on the analysis of a 40 yr numerical hindcast (1979–2016).

Climate change is expected to have a signature in storm surge intensity, frequency, and/or timing. However, existing studies did not find clear trends in storm surge intensity over the North Atlantic. Storm surges show a strong annual cycle, with larger values in winter, the maximum occurring in December or January along the European coasts (Menéndez & Woodworth, 2010). Here, we focus on possible changes in terms of timing of maximum storm surges. This has seldom been investigated for storm surges, but it has been for other processes like river floods. While there is no consistent large-scale change in flood magnitudes, there are indeed clear shifts in European flood timing (Blöschl et al., 2017). Later winter floods occur around the North Sea and parts of the Mediterranean Sea due to delayed winter storms associated with polar warming (Blöschl et al., 2017).

The objective of this article is to investigate if there is a shift in the timing of storm surges over the last decades. We focus on one of the world's longest records located in Brest (France), which covers the period 1846–2018 with hourly data. Our main tool for the analysis of storm surges is statistical extreme value theory.

The article is organized as follows. The first section below describes the sea level data. The following section presents our methods. We then present our results, with a particular focus on the seasonality of storm surge and the observed shift in the timing of extreme events. We finally discuss the possible reasons that may explain this shift of the storm season.

2. Sea Level Data

The sea level data used in our study are hourly tide gauge measurements in the harbor of Brest from 1846 to 2018, located in the North East Atlantic (Figure 1). This station has benefited from important efforts to recover, digitalize, and quality control historical data, which allowed to extend the time series back to the early 18th century (Pouvreau, 2008; Pouvreau et al., 2006; Wöppelmann et al., 2006). It is the longest sea level record in France (Wöppelmann et al., 2008) and one of the longest worldwide (Woodworth et al., 2011). We retrieved the tide gauge data from the website of the French Hydrographic and Oceanographic Service SHOM (https://data.shom.fr/, accessed in October 2019), which provides hourly data starting in 1846. Before 1846, the sea level in Brest was measured manually (not with an automatic tide gauge), so the data do not have the same high temporal resolution and are thus not of interest for our study (Wöppelmann et al., 2006).

From the sea level data, we computed surge levels, which can be defined in two different ways. (a) The “skew surge” is the difference between the maximum observed sea level and the maximum tide prediction during a tidal cycle (Pugh & Woodworth, 2014); as these two maxima may occur with an offset of some minutes, this calculation is “askew”. (b) In contrast, the more traditional “non-tidal residual” is the instantaneous difference between the observed sea level and the predicted sea level. We focus here on skew surge instead of the non-tidal residual, because it avoids a possibly imperfect separation of tidal and non-tidal components that would result from timing errors in the observation (Marcos & Woodworth, 2017).

We computed the tide using the MAS program (Simon, 2007, 2013) developed by the French Hydrographic Office SHOM. The tide and the MSL were computed yearly. The MSL is the annual MSL, averaged from the observations. We chose to analyze the data yearly (rather than on the overall period) to ensure that changes in MSL (particularly the MSL rise) and changes in the tide are not part of the computed surge levels. Indeed, the tide has changed due to non-astronomical factors since the 19th century (Haigh et al., 2019; Talke & Jay, 2020), and the amplitude of the M_2 tidal constituent at Brest changed by more than 4 cm over the period 1846–2018 (Pineau-Guillou et al., 2021). However, the drawback of this method is that the yearly computed harmonic constituents are less resolved than in a longer tidal analysis (e.g., over 15 yr as in the study of Marcos & Woodworth, 2017). For the yearly analysis, we excluded years with less than 300 full days of measurements to ensure a reliable tidal analysis without seasonal bias. Indeed, in the North Atlantic, M_2 is affected by a seasonal variation of a few percent (Gräwe et al., 2014; Müller et al., 2014). Excluding years with less than 300 full days leaves us with 156 calendar years of data. The program computes up to 541 harmonic components. Every year, between 191 and 257 components were computed, depending on the data completeness. The nodal corrections were included in the prediction, to take into account the 18.6 yr nodal cycle. We made sure to take off the harmonic constituent S_a for the prediction. This annual component does not correspond to the astronomical tide, but to the radiational tide, reflecting the variations associated with thermal effects of solar radiation on the atmosphere and the ocean (Simon, 2007, 2013).

10.1029/2021JC017794

Finally, we computed the skew surge as the difference between the observed and predicted high tide. The observed water levels at high tide were computed by interpolating the hourly data with a parabola, also using the MAS tool of SHOM.

To check if our observations are large-scale, we used the Global Extreme Sea Level Analysis data set, Version 2 (GESLA-2; Marcos & Woodworth, 2017; Woodworth et al., 2017), provided on https://gesla.org/. This data set contains skew surge records at 1,355 stations worldwide, of which we selected the nine records at the European coasts of the open Atlantic Ocean that start in the first half of the 20th century or earlier (Figure 1). When using the GESLA-2 skew surge, we must take into account that these surge levels contain the MSL rise, because a single tidal analysis was used to compute the skew surge (Marcos & Woodworth, 2017), not a separate one for every year (see Section 4.4).

3. Methods

There are two main methods for statistical modeling of extreme values, either based on block maxima or peaks over a threshold (Coles, 2001). The latter approach relies on the arbitrary choice of a threshold, but a small variation of the threshold can lead to large differences in the estimated parameters. To avoid this possible error source, we used block maxima.

We chose a block size of one month and selected for each month in our time series the highest observed skew surge level (similar to Menéndez & Woodworth, 2010). This gives us the set of monthly maxima z_t (with time index t), which we consider as realizations of a random variable Z_t. According to Coles (2001), we can expect this random variable to come from a generalized extreme value (GEV) distribution: $Z_t \sim \mathrm{GEV}(\mu(t), \sigma(t), \xi)$. The cumulative distribution function of the GEV distribution is:

$$F(z_t; \mu(t), \sigma(t), \xi) = \exp\left\{ -\left[1 + \xi\left(\frac{z_t - \mu(t)}{\sigma(t)}\right)\right]^{-1/\xi} \right\} \tag{1}$$

with location parameter $\mu(t)$, scale parameter $\sigma(t) > 0$, and shape parameter ξ, where an appropriate limit for the case $\xi = 0$ yields the Gumbel distribution (Coles, 2001). Note that the shape parameter ξ has no time-dependence in our model, because this parameter is generally difficult to estimate (Coles, 2001) and does not vary substantially with time (Davison & Ramesh, 2000; Marcos et al., 2015; Marcos & Woodworth, 2017).

To account and test for climatic influences on extreme surge levels, we used time-dependent parameters for the GEV distribution and modeled the location parameter μ as (compare Menéndez & Woodworth, 2010):

$$\mu(t) = \mu_0 + \mu_1 t + \mu_2 \cos(\omega t) + \mu_3 \sin(\omega t) + \mu_4\, \mathrm{NAO}(t). \tag{2}$$

The coefficient μ_1 tests for a linear trend, i.e., a long-term in-/decrease of surge. The harmonic oscillation (μ_2, μ_3) with $\omega = 2\pi\ \mathrm{yr}^{-1}$ accounts for the important annual cycle of surge (Menéndez & Woodworth, 2010). The last coefficient (μ_4) takes into account the effect of the NAO, a large-scale climate pattern that influences pressure, temperature, and rainfall in Europe (Visbeck et al., 2001), and thus also impacts surge levels (Marcos & Woodworth, 2017). We used for NAO(t) the monthly index provided by NOAA (Jones et al., 1997) on https://psl.noaa.gov/gcos_wgsp/Timeseries/. We modeled the scale parameter σ as:

$$\sigma(t) = \sigma_0 + \sigma_1 t + \sigma_2 \cos(\omega t) + \sigma_3 \sin(\omega t) + \sigma_4\, \mathrm{NAO}(t), \tag{3}$$

analogue to Equation 2, and we ensured that $\sigma(t) > 0$ holds for all t within the data set.

We determined the parameters of our GEV model with the maximum likelihood method as described by Coles (2001), which also gives the standard error of each parameter estimate *via* the delta method (Coles, 2001). Then we checked which parameters contribute significantly to the model, using a test based on the deviance statistic (Coles, 2001) at the $\alpha = 5\%$-level of significance.

The annual oscillations $\mu_2\cos(\omega t) + \mu_3\sin(\omega t)$ and $\sigma_2\cos(\omega t) + \sigma_3\sin(\omega t)$ used in our model are a special case of the model used in the global analysis of surge records by Menéndez and Woodworth (2010). The difference is that their (global) model also contains semi-annual cycles, which are relatively small in Brest: In our 156 yr data set, the semi-annual cycle in μ has an amplitude of about 2 cm, which is much less than the 11 cm amplitude of the annual cycle; the amplitudes for σ are 0.1 and 5 cm, respectively (see also Section 4.3). Thus, we excluded semi-annual cycles from our analysis.

To analyze changes in the seasonality of extreme surge levels, we applied the time-dependent GEV model in two ways. The first way is a "sliding window analysis" (method 1): We fitted the GEV model described above to every 30 yr window with at least 50% of data completeness (i.e., we considered every continuous period of 30 yr that contains 180 monthly maxima or more). In each window, we analyzed the phase of the seasonal oscillation, that means, the timing of the maximum of $\mu_2 \cos(\omega t) + \mu_3 \sin(\omega t)$, cf. Equation 2. This represents the timing of extreme surge events in the year. We verified that our results do not change much when we take a different window size, apart from increased interannual variability and uncertainties for shorter windows.

Our second way is a "monthly analysis" (method 2): For a given period, we fitted a separate GEV model for every calendar month, thereby obtaining 12 models. In this case, there is no need for an annual cycle as only a single month is considered, so μ_2 and μ_3 in Equation 2 are set to zero, as well as $\sigma_2 = \sigma_3 = 0$ in Equation 3. As will be seen later (Section 4.2), the linear NAO-contribution is relatively weak for our Brest data set, so that we can reduce the GEV parameters in method 2 to:

$$\mu^{(m)}(t) = \mu_0^{(m)} + \mu_1^{(m)} t\,, \quad \sigma^{(m)}(t) = \sigma_0^{(m)} + \sigma_1^{(m)} t\,, \quad \xi^{(m)}\,, \quad m \in \{\text{Jan}, \text{Feb}, \ldots, \text{Dec}\}\,. \tag{4}$$

This method enables us to test if, over a given, long period, surge levels declined in one of the months and increased in another, thus indicating a possible shift in the timing of extreme surge events. We will evaluate in method 2 also the mean value of the extreme surge distribution, which is given by Muraleedharan et al. (2011) as:

$$\hat{\mu}^{(m)} + \hat{\sigma}^{(m)}[\Gamma(1 - \hat{\xi}^{(m)}) - 1]/\hat{\xi}^{(m)} \tag{5}$$

with the gamma function Γ. The mean is well-defined if $\hat{\xi}^{(m)} < 1$.

Note that method 2 has more free parameters than method 1 and can consequently be used to test for other changes in the seasonality of extremes, not only timing shifts, but this is beyond the scope of this article. The Python code that the authors developed for their analysis is freely available on https://doi.org/10.5281/zenodo.5674878.

4. Results

4.1. Long-Term Trends

At first, we investigated long-term trends in our tide gauge record, to understand how the data generally evolved. We calculated the annual MSL, the annual 99th percentile of the full sea level (including MSL, tide, and surge), and the annual 99th percentile of surge levels (blue graphs in Figure 2), as well as the linear trend in each of these three-time series (black dashed lines in Figure 2) using linear regression. We verified that the residuals of the regressions are normally distributed, using the Shapiro-Wilk test as well as the D'Agostino-Pearson test with $\alpha = 0.05$.

Our first result is that the extreme sea level trend is close to the MSL trend in Brest with values of (11.5 ± 1.2) cm per century and (12.5 ± 0.6) cm per century, respectively (dashed black lines in Figures 2a and 2b). This is consistent with previous studies, which found that the MSL rise is the main reason for increased extreme sea levels (Marcos & Woodworth, 2017; Menéndez & Woodworth, 2010).

Our second result is that there is no significant long-term trend in extreme surge levels in Brest: Linear regression yields an increase of (1.1 ± 0.9) cm per century, which is not significant and much smaller than the interannual variability (Figure 2c). Our time-dependent GEV analysis of monthly surge maxima from 1846 to 2018 confirms that the linear trend is not statistically significant ($\alpha = 5\%$); the estimated values are $\hat{\mu}_1 = (-0.8 \pm 0.4)$ cm per century and $\hat{\sigma}_1 = (0.1 \pm 0.3)$ cm per century (cf. Equations 2 and 3). The absence of a linear trend in extreme surges is in agreement with previous studies (Marcos & Woodworth, 2017; Mawdsley & Haigh, 2016). However, this does not exclude the possibility of linear trends over shorter time periods, like those considered in Section 4.3 below.

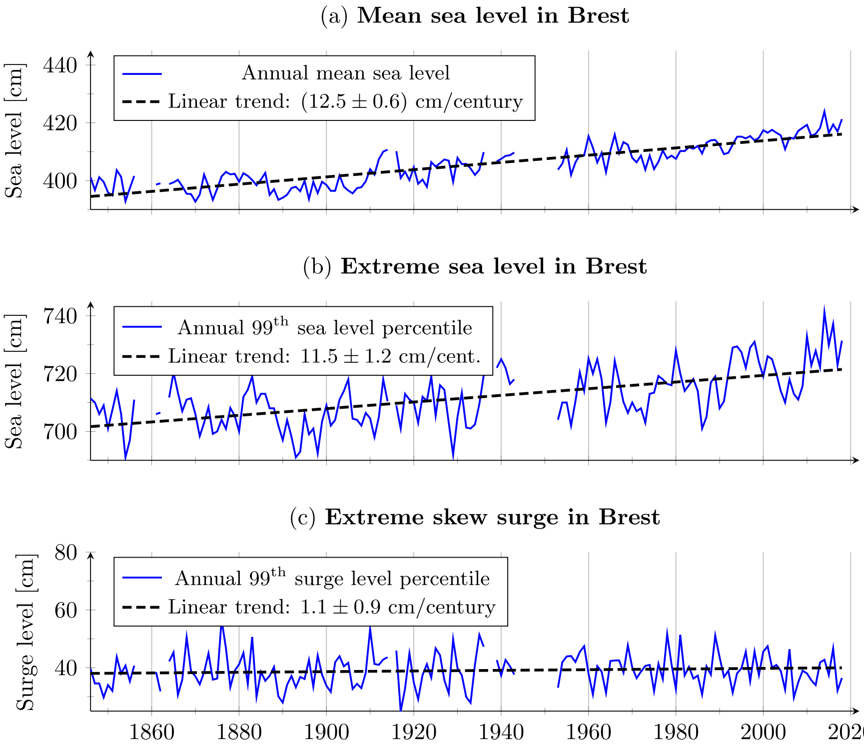

Figure 2. Time series of annual (a) mean sea level, (b) extreme sea level, and (c) extreme surge level in Brest from 1846 to 2018, and their overall trends.

Note that our sea level record contains gaps, as can be seen in Figure 2. The longest and latest was from May 1, 1944 to December 31, 1952, because big parts of the Brest harbor and in particular the tide gauge were destroyed during World War II (Wöppelmann et al., 2006).

4.2. NAO Influence

From our time-dependent GEV-analysis of monthly surge maxima in Brest between 1846 and 2018, we also obtained estimates for the coefficients μ_4 and σ_4, which stand for the influence of the NAO on the extreme surge distribution (cf. Equations 2 and 3). We found that the influence is statistically significant, but of relatively small amplitude for typical NAO values. The numerical values are $\hat{\mu}_4 = (-0.4 \pm 0.2)$ cm and $\hat{\sigma}_4 = (-0.2 \pm 0.1)$ cm per unit of the NAO index. The negative sign in both coefficients means that high surge events are less likely in times of positive NAO, and *vice versa,* consistent with the study of Menéndez and Woodworth (2010). Because of the small amplitude of the NAO influence, we set $\mu_4 = \sigma_4 = 0$ later on, to focus on a much stronger contribution: the annual cycle. Nevertheless, we verified that our main results remain unchanged even if NAO is included in the model.

4.3. Annual Cycle

In our GEV-based analysis of the complete time series, we observed that the annual cycle of surge levels is large for Brest. The amplitudes of the annual oscillations in the GEV parameters are $(\hat{\mu}_2^2 + \hat{\mu}_3^2)^{1/2} = (11.4 \pm 0.4)$ cm and $(\hat{\sigma}_2^2 + \hat{\sigma}_3^2)^{1/2} = (4.7 \pm 0.3)$ cm (uncertainties were calculated with the delta method together with the standard formula for error propagation). The estimated location parameter $\hat{\mu}(t)$ reaches its maximum in mid-December, the scale parameter $\hat{\sigma}(t)$ in late January, so they vary asynchronously, and the most extreme surge events typically occur in winter. The effect of this seasonal oscillation is that the estimated 100 yr return surge level (defined as z such that $F(z; \hat{\mu}, \hat{\sigma}, \hat{\xi}) = 1 - 1/100$ with F from Equation 1, cf. Coles, 2001) is less than 50 cm in summer, but more than 110 cm in winter.

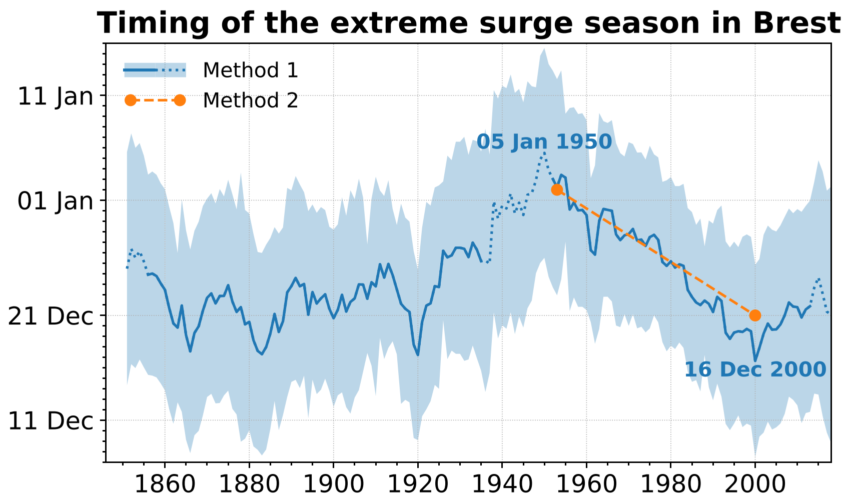

Figure 3. Date of the year when the highest extreme surge is expected, with respect to the location parameter μ. The blue graph (method 1) is dotted in periods with less than 20 yr of data per 30 yr window; the shaded area marks the 95% confidence interval, computed with the delta method (Coles, 2001). The dashed orange line (method 2) shows the linear shift between January 2, 1953 and December 21, 2000, the dates in the middle of the extreme surge season of these two years.

Then we employed our 30 yr sliding window analysis (method 1) with the above-mentioned simplification that $\mu_4 = \sigma_4 = 0$. We calculated the day of the year at which the annual oscillation in μ reaches its maximum, which represents the typical timing of extreme surge events (blue graph in Figure 3). In most of our time series, the maximum of extreme surge events appears in the second half of December, with a 95% confidence interval spanning 2–3 weeks. In the 1950s, however, the extreme surge season peaks in the first week of January. In the following decades, the extreme surge timing makes a clear, directed shift forward. This causes extreme surge events to occur almost three weeks earlier in the year 2000 than in the year 1950. While the 95% confidence intervals for the dates of the surge maximum in these two years are not disjoint, the best estimate for the date in 1950 lies clearly outside the uncertainty bound of the date in 2000 and *vice versa*. There is some indication of a reversed trend in the current century, but the two decades of data since 2000 are not sufficient to categorize this as a long-term trend.

In the following, we focus on the distinct shift of the extreme surge season that happened between 1950 and 2000. We can confirm this shift with our monthly analysis (method 2, dashed orange line in Figure 3). We applied method 2 over the period 1953–2000, because there are no data for 1944–1952 (cf. Figure 2) due to the destruction of the tide gauge in World War II (Wöppelmann et al., 2006).

In our monthly analysis (method 2), which uses a separate model for every calendar month, we found that at the beginning of winter, in October, the linear trend $\mu_1^{(m)}$ is strongly positive, while at the end of winter, in March, it is significantly negative ($\alpha = 0.05$), see Table 1. This has the effect that in the 1950s, the season of highest surge levels lasts from November to March, whereas half a century later, this season is from October to January, see Figure 4, which shows this shift of the extreme surge season in terms of the mean of the GEV distribution (note that the mean is well-defined because $\hat{\xi}^{(m)} < 1$ holds for all months m, see Table 1). To quantify this shift accurately, we calculated the date of mid-winter by weighting every day of the winter months October–March with its corresponding $\hat{\mu}^{(m)}$-value: in 1953, the extreme surge season is centered around January 2, whereas in the year 2000, its mid-point is December 21. This is similar to the shift of three weeks that we found with method 1 (Figure 3).

We checked that the strong increase of the location parameter $\mu^{(\mathrm{Oct})}$ in October is not sensitive to a single big event. The highest skew surge in Brest

Table 1
GEV Parameters of our Monthly Analysis (Method 2) for Brest

	$\hat{\mu}_0^{(m)}$	$\hat{\mu}_1^{(m)}$	$\hat{\sigma}_0^{(m)}$	$\hat{\sigma}_1^{(m)}$	$\hat{\xi}^{(m)}$
January	35 ± 4	-10 ± 28	14 ± 3	7 ± 17	-0.29 ± 0.21
February	28 ± 6	-14 ± 32	18 ± 4	-10 ± 21	-0.22 ± 0.19
March	30 ± 3	-43 ± 16	13 ± 3	-6 ± 7	-0.57 ± 0.21
April	17 ± 4	4 ± 23	12 ± 3	-7 ± 15	-0.20 ± 0.18
May	15 ± 3	-13 ± 17	8 ± 2	-1 ± 15	-0.15 ± 0.22
June	13 ± 2	-14 ± 13	6 ± 2	7 ± 10	0.02 ± 0.29
July	11 ± 3	-9 ± 14	7 ± 2	-5 ± 11	-0.16 ± 0.19
August	14 ± 2	-10 ± 14	6 ± 1	4 ± 8	-0.09 ± 0.15
September	18 ± 3	22 ± 22	9 ± 2	4 ± 15	-0.03 ± 0.28
October	29 ± 3	21 ± 23	10 ± 3	11 ± 20	0.11 ± 0.20
November	36 ± 6	-16 ± 35	16 ± 4	-13 ± 22	-0.07 ± 0.19
December	36 ± 6	-4 ± 36	16 ± 4	-5 ± 23	-0.10 ± 0.30

Note. Values of $\hat{\mu}_0^{(m)}$ and $\hat{\sigma}_0^{(m)}$ are in cm. Values of $\hat{\mu}_1^{(m)}$ and $\hat{\sigma}_1^{(m)}$ are in cm per century. Values after ± denote the extent of the 95% confidence intervals. Confidence intervals were obtained with the delta method. The epoch (that means $t = 0$ in Equation 4) is on 1970-01-01.

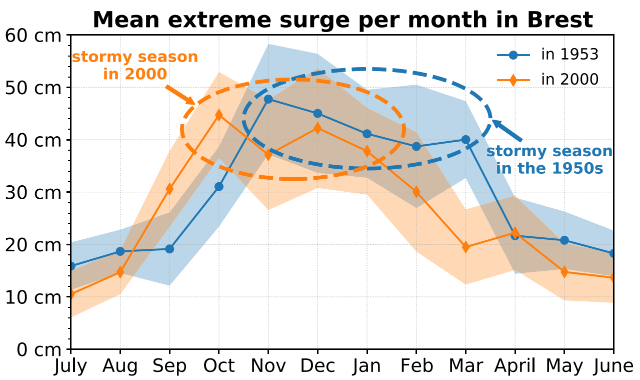

Figure 4. Comparison of the mean extreme surge in each month at the beginning and at the end of the seasonal shift, computed with our monthly analysis with linear trends (method 2). The dashed ellipses highlight what can be considered the high surge or "stormy" season. Shaded areas mark the 95% confidence interval, computed with the delta method (Coles, 2001) together with the standard formula for error propagation. Note that 1953 was chosen instead of 1950 because the years 1944–1952 are missing in the tide gauge record of Brest.

(138 cm) was recorded during the Great Storm of October 1987. We verified that without this year, the increase of the location parameter in October is similar.

4.4. Seasonal Shift in Other Stations

To go further, we investigated if the observed seasonal shift between 1950 and 2000 was a large-scale process—and not just limited to Brest—by analyzing the relevant nine long-term skew surge records of the GESLA-2 data set (Figure 1). We focused on the months March and October, which showed for Brest strong opposite trends of the location parameter (Table 1). For each of the two months, we fitted to its monthly maxima over the period 1950–2000 a GEV distribution with the linearly time-dependent parameters of method 2 (Equation 4). This way, we obtained monthly linear trends $\mu_1^{(m)}$ for March and October. Since the GESLA-2 surge levels contain the MSL rise (Marcos & Woodworth, 2017), we must correct for this bias. For this, we subtracted from the monthly trends $\mu_1^{(m)}$ the yearly trend $\mu_1^{(y)}$ (μ_1 of Equation 2 fitted on the monthly maxima of the whole years). Consequently, we looked at trends in March and October relative to the trend in all 12 months, $\mu_1^{(m)} - \mu_1^{(y)}$. The results are presented in Figure 5, expressed as centimeter per 50 yr, which is exactly the relative change over our study period 1950–2000.

Apart from one exception discussed later (Saint-Jean-de-Luz), the relative change in October is positive everywhere (red circles in Figure 5). This means that extreme surge levels have increased more during October than over the whole year. In contrast to that, the extreme surge levels in March have decreased relative to the yearly trend, so the relative change is negative (blue diamonds in Figure 5). For the stations in Cherbourg, Le Havre, and La Rochelle, where the data coverage is less complete, the 95% confidence intervals of the estimated trends are quite wide, but the agreement with the trends in the other stations is nevertheless remarkable. We did the analysis for Brest with the GESLA-2 data set as well as with our own surge data, and the results are consistent (Figure 5). The fact that the trends in all other stations are similar to those in Brest suggests that the observed shift is indeed a large-scale process impacting a big part of the European Atlantic coast.

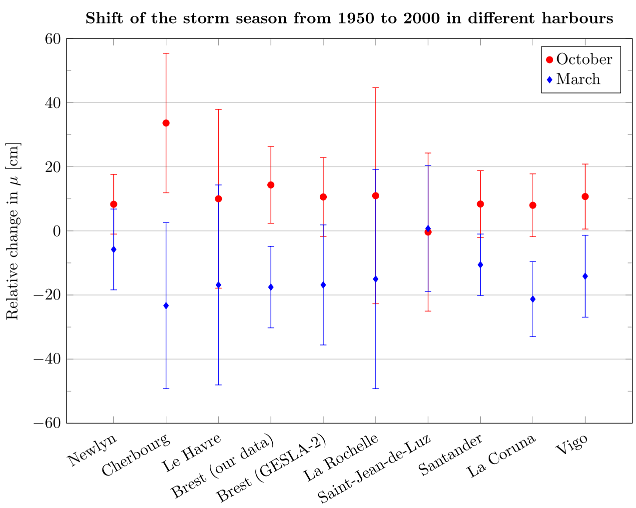

Figure 5. Change in the GEV location parameter μ for surge maxima of October (red circles) and March (blue diamonds) relative to the yearly change, in different harbors at the European Atlantic coast, for the period 1950–2000, and their 95% confidence intervals. The stations are sorted from North to South, cf. Figure 1 for their locations. Confidence intervals were computed with the delta method (Coles, 2001) together with the standard formula for error propagation.

The only exception is the station Saint-Jean-de-Luz in southern France near the Spanish border, which shows practically no trends. Interestingly, the same pattern was reported regarding river floods (Blöschl et al., 2017): They arrive earlier in parts of the European Atlantic region, except for an area around the Spanish-French border. However, Blöschl et al. (2017) attributed the earlier floods to an earlier soil moisture maximum, rather than earlier winter storms.

5. Discussion

The possible causes for the seasonal shift of storm surges are still unknown. However, any change in the large-scale atmospheric circulation, such as changes in storminess or storm tracks, may affect storm surges. The review by Feser et al. (2015) about the potential long-term trends in storminess over the North Atlantic and northwestern Europe, taking into account measurements, reanalyzes, and climate models, came to the conclusion that the trends in storm activity depend critically on the time period analyzed: While storm numbers increased for the most recent decades, there was merely decadal variability over the last 100–150 yr. A study on the evolution of North East Atlantic storminess since the late 19th century found that storm activity increased from the 1960s on and has been decreasing since the 1990s (Krueger et al., 2019). However, the 1990s peak in storm activity has been reported to be similar to that of the late 19th century, and long-term storminess has returned now to average values in recent years (Krueger et al., 2019), which

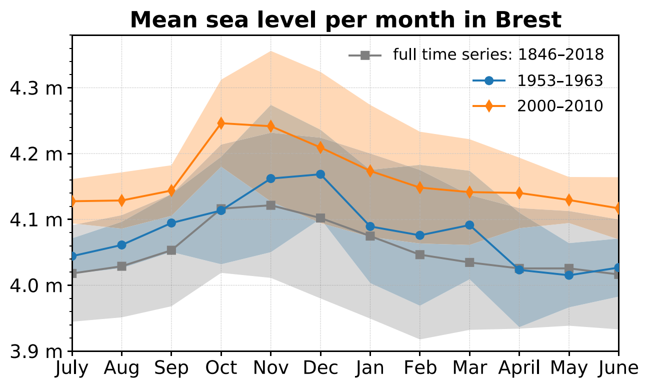

Figure 6. Monthly mean sea level in Brest computed over the periods 1846–2018, 1953–1963, and 2003–2013. Shaded areas show the standard deviation of the monthly means in the considered period. Note that 1953 was chosen instead of 1950 because the years 1944–1952 are missing in the tide gauge record of Brest.

suggests an important role of the multidecadal variability. Regarding these results and the fact that the timing of our seasonal maximum appears to be increasing since the year 2000 (Figure 3), the observed shift over the period 1950–2000 could be partly linked to multidecadal variability rather than a long-term trend (which one could think if only the 50 yr of data between 1950 and 2000 were available). In addition to changes in storminess, changes in storm tracks could also impact storm surges. For example, in the western North Pacific, Oey and Chou (2016) found evidence for a northward shift of storm surge, due to a poleward shift in the location of the intensity maximum of tropical cyclones in recent decades. Dedicated studies should be undertaken to understand the physical causes behind the observed seasonal shift in Brest and in parts of the European Atlantic coast. They could be based on novel data-driven causal methods (Runge et al., 2019) in addition to numerical modeling.

The observed shift in the annual cycle of extreme surge levels could also come partly from changes in the regional seasonality of the MSL, due to variations of temperature and salinity (steric effects). At Brest, the monthly MSL averaged over the full time series (1846–2018) shows an annual cycle with an amplitude of around 5 cm and a maximum in November (Figure 6). When we consider only the period 1953–1963, which is the beginning of the seasonal shift in extreme surge levels, this maximum occurred in December (Figure 6). But for the period 2000–2010, after the seasonal shift, the maximum was in October (Figure 6). So also the seasonality of MSL has undergone a shift to earlier times between the 1950s and the start of the 21st century. To investigate the influence of the MSL seasonality on our results, we processed the skew surge data removing monthly MSL instead of annual MSL. We observed that although the maximum of the annual cycle is a few days later over every period, the seasonal shift between the 1950s and the 2000s is still there and even slightly stronger (25 instead of 20 days; see Figure S1). Furthermore, Figure 7 shows amplitude and phase of the annual cycle in extreme surge levels, removing either annual or monthly MSL. The mean amplitude of the annual cycle is 11.3 cm removing annual MSL (Figure 7a), compared to 8.0 cm removing monthly MSL (Figure 7b). This suggests a relatively small contribution (around 3 cm) of the MSL seasonality to the annual cycle of extreme surge levels (total amplitude of around 11 cm). Figure 7b shows that after removing the MSL seasonality, the interannual variability is reduced, but the seasonal shift between the 1950s and the 2000s is still pronounced.

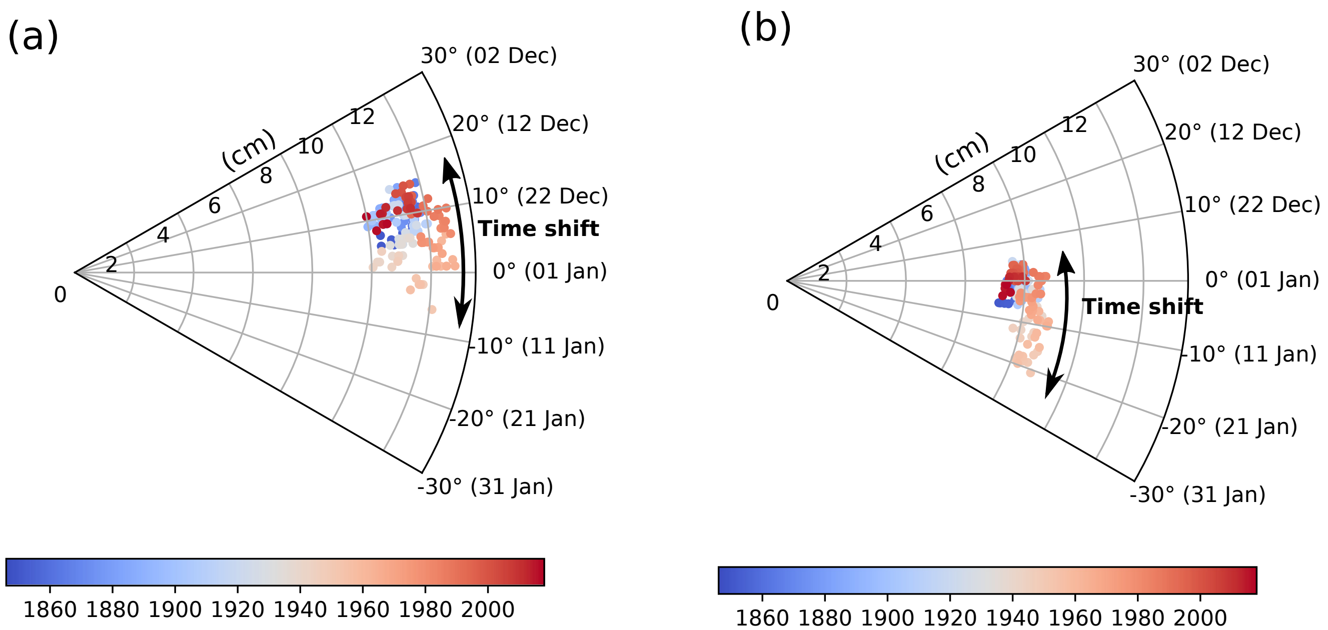

Figure 7. Amplitude and phase of the annual cycle in extreme surge levels in Brest after removing (a) annual mean sea level, or (b) monthly mean sea level.

Furthermore, other variables than storm surges show similarly a seasonal time shift. Regarding river floods, a clear shift in Europe over the period 1960–2010 was reported: In Western Europe along the Atlantic coast, river floods come 3–8 days earlier, due to an earlier soil moisture maximum (Blöschl et al., 2017). The driver invoked for this is different from the one of storm surge (soil moisture vs. large-scale atmosphere circulation), but in some regions, the timing of the maximum soil moisture is closely aligned with the one of precipitation (e.g., northwestern Iberia, see Blöschl et al., 2017), whose driver is also the large-scale atmospheric circulation. However, the maxima of soil moisture and precipitation are not always aligned (e.g., southern England, see Blöschl et al., 2017). Regarding surface temperature, Stine et al. (2009) found a time shift in the annual cycle of surface temperature, with on average 1.7 days earlier seasons over extratropical land in 2007 compared to 1954. The North Atlantic exhibits trends toward earlier seasons south of 50°N, but north of 50°N the trends are toward later seasons (around 3 days), according to Stine et al. (2009). These shifts in the annual cycles appear to be related, in part, to changes in the atmospheric circulation, as suggested by significant correlations between time series and climate indices (Stine et al., 2009). However, the causes of these changes remain poorly understood, partly because of a lack of understanding of the natural variability (Stine et al., 2009).

6. Conclusion

We investigated changes in the timing of storm surge events in Brest, using two different methods based on statistical extreme value analysis. The first method consists of fitting a GEV distribution with time-dependent parameters reproducing an annual cycle to yearly data, whereas the second method consists of fitting a GEV distribution with time-dependent parameters reproducing a linear trend to monthly data. Both methods give consistent results.

We found that the season of extreme surge levels shifted by about three weeks forward over the second half of the 20th century in Brest (Figures 3 and 4). Since the year 2000, there appears to be the opposite trend, which suggests a link with multidecadal variability rather than a long-term trend. We also found evidence that the seasonal shift in the period 1950–2000 did not only happen in Brest but impacted a large part of the European Atlantic coast (Figure 5). As the physical causes for this large-scale change of extreme surge timing have not been fully understood yet, further research is required.

Detecting shifts in the storm surge season can be important, as storm surges and waves greatly impact the ecosystems. Storm events can increase mortality of benthic species, due to movements (i.e., erosion, deposition) of the substratum where the benthos live (Zhang et al., 2021). For the south of the North Sea, Nehls and Thiel (1993) reported that the number of mussel beds were divided by nearly two between 1989 and 1990, due to severe storms in early 1990. For the Gulf of Mexico, Posey et al. (1996) reported that one third of benthic fauna exhibited a significant decline after a severe storm. Along the coasts of China, Zhang et al. (2021) reported strong mortality of shellfish (clams) during storms. These studies underline the vulnerability of benthic species to storm events. A shift of the storm season that would coincide with periods of reproduction of benthic organisms (e.g., January or February for the mussels in the North Atlantic) may have severe environmental and economic consequences.

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Data Availability Statement

The Python code that the authors developed and used for the statistical extreme surge level analysis presented in this article can be downloaded from https://doi.org/10.5281/zenodo.5674878.

References

Bertin, X., Li, K., Roland, A., Zhang, Y. J., Breilh, J. F., & Chaumillon, E. (2014). A modeling-based analysis of the flooding associated with Xynthia, central Bay of Biscay. *Coastal Engineering*, *94*, 80–89. https://doi.org/10.1016/j.coastaleng.2014.08.013

Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., et al. (2017). Changing climate shifts timing of European floods. *Science*, *357*(6351), 588–590. https://doi.org/10.1126/science.aan2506

Coles, S. (2001). *An introduction to statistical modeling of extreme values*. Springer. https://doi.org/10.1007/978-1-4471-3675-0

Dangendorf, S., Arns, A., Pinto, J. G., Ludwig, P., & Jensen, J. (2016). The exceptional influence of storm "Xaver" on design water levels in the German bight. *Journal of Climate*, *11*(5), 054001. https://doi.org/10.1088/1748-9326/11/5/054001

Davison, A. C., & Ramesh, N. I. (2000). Local likelihood smoothing of sample extremes. *Journal of the Royal Statistical Society: Series B*, *62*(1), 191–208. https://doi.org/10.1111/1467-9868.00228

Fernández-Montblanc, T., Vousdoukas, M., Mentaschi, L., & Ciavola, P. (2020). A Pan-European high resolution storm surge hindcast. *Environment International*, *135*, 105367. https://doi.org/10.1016/j.envint.2019.105367

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R., & Xia, L. (2015). Storminess over the North Atlantic and northwestern Europe—A review. *Quarterly Journal of the Royal Meteorological Society*, *141*, 350–382. https://doi.org/10.1002/qj.2364

Genovese, E., & Przyluski, V. (2013). Storm surge disaster risk management: The Xynthia case study in France. *Journal of Risk Research*, *16*(7), 825–841. https://doi.org/10.1080/13669877.2012.737826

Gräwe, U., Burchard, H., Müller, M., & Schuttelaars, H. M. (2014). Seasonal variability in M_2 and M_4 tidal constituents and its implications for the coastal residual sediment transport. *Geophysical Research Letters*, *41*(15), 5563–5570. https://doi.org/10.1002/2014GL060517

Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., et al. (2019). The tides they are a-changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms, and future implications. *Reviews of Geophysics*, *57*, e2018RG000636. https://doi.org/10.1029/2018RG000636

Hurrell, J. W., & Deser, C. (2009). 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

IPCC. (2013). In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 1535). Cambridge University Press.

IPCC. (2014). In Core Writing Team., In R. K. Pachauri, & L. A. Meyer (Eds.), *Climate change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 151). IPCC.

IPCC. (2021). In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Ji, T., Li, G., & Zhang, Y. (2019). Observing storm surges in China's coastal areas by integrating multi-source satellite altimeters. *Estuarine, Coastal and Shelf Science*, *225*, 106224. https://doi.org/10.1016/j.ecss.2019.05.006

Jones, P. D., Jonsson, T., & Wheeler, D. (1997). Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *International Journal of Climatology*, *17*(13), 1433–1450. https://doi.org/10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P

Krueger, O., Feser, F., & Weisse, R. (2019). Northeast Atlantic storm activity and its uncertainty from the late 19th to the 21st century. *Journal of Climate*, *32*(6), 1919–1931. https://doi.org/10.1175/JCLI-D-18-0505.1

Marcos, M., Calafat, F. M., Berihuete, Á., & Dangendorf, S. (2015). Long-term variations in global sea level extremes. *Journal of Geophysical Research: Oceans*, *120*(12), 8115–8134. https://doi.org/10.1002/2015JC011173

Marcos, M., & Woodworth, P. L. (2017). Spatiotemporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, *122*(9), 7031–7048. https://doi.org/10.1002/2017jc013065

Mawdsley, R. J., & Haigh, I. D. (2016). Spatial and temporal variability and long-term trends in skew surges globally. *Frontiers in Marine Science*, *3*, 29. https://doi.org/10.3389/fmars.2016.00029

Menéndez, M., & Woodworth, P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research: Oceans*, *115*. https://doi.org/10.1029/2009jc005997

Müller, M., Cherniawsky, J. Y., Foreman, M. G. G., & von Storch, J. S. (2014). Seasonal variation of the M_2 tide. *Ocean Dynamics*, *64*, 159–177. https://doi.org/10.1007/s10236-013-0679-0

Muraleedharan, G., Soares, C. G., & Lucas, C. (2011). Characteristic and moment generating functions of generalized extreme value distribution (GEV). In *Sea level rise, coastal engineering, shorelines and tides* (pp. 269–276). Nova.

Nehls, G., & Thiel, M. (1993). Large-scale distribution patterns of the mussel mytilus edulis in the Wadden sea of Schleswig-Holstein: Do storms structure the ecosystem? *Netherlands Journal of Sea Research*, *31*, 181–187. https://doi.org/10.1016/0077-7579(93)90008-G

Oey, L.-Y., & Chou, S. (2016). Evidence of rising and poleward shift of storm surge in western North Pacific in recent decades. *Journal of Geophysical Research: Oceans*, *121*, 5181–5192. https://doi.org/10.1002/2016JC011777

Pineau-Guillou, L., Lathuiliere, C., Magne, R., Louazel, S., Corman, D., & Perherin, C. (2012). Sea levels analysis and surge modeling during storm Xynthia. *European Journal of Environmental and Civil Engineering*, *16*(8), 943–952. https://doi.org/10.1080/19648189.2012.676424

Pineau-Guillou, L., Lazure, P., & Wöppelmann, G. (2021). Large-scale changes of the semidiurnal tide along North Atlantic coasts from 1846 to 2018. *Ocean Science*, *17*, 17–34. https://doi.org/10.5194/os-17-17-2021

Posey, M., Lindberg, W., Alphin, T., & Vose, F. (1996). Influence of storm disturbance on an offshore benthic community. *Bulletin of Marine Science*, *59*(3), 523–529.

Pouvreau, N. (2008). *Trois cents ans de mesures marégraphiques en France: Outils, méthodes et tendances des composantes du niveau de la mer au port de brest*. University of La Rochelle. (Ph.D. thesis, University of La Rochelle).

Pouvreau, N., Miguez, B. M., Simon, B., & Wöppelmann, G. (2006). Évolution de l'onde semi-diurne M_2 de la marée à Brest de 1846 à 2005. *Comptes Rendus Geoscience*, *338*, 802–808. https://doi.org/10.1016/j.crte.2006.07.003

Pugh, D., & Woodworth, P. (2014). *Sea level science: Understanding tides, surges, tsunamis and mean sea level changes*. Cambridge University Press.

Runge, J., Bathiany, S., Bollt, E., Camps-Valls, G., Coumou, D., Deyle, E., et al. (2019). Inferring causation from time series in Earth system sciences. *Nature Communications*, *10*, 2553. https://doi.org/10.1038/s41467-019-10105-3

Simon, B. (2007). *La marée océanique côtière*. Institut Océanographique Ed. Retrieved from https://iho.int/iho_pubs/CB/C-33/C-33_maree_simon_fr.pdf

Simon, B. (2013). *Coastal tides*. Institut Océanographique Ed. Retrieved from https://iho.int/iho_pubs/CB/C-33/C-33_maree_simon_en.pdf

Stine, A., Huybers, P., & Fung, I. (2009). Changes in the phase of the annual cycle of surface temperature. *Nature*, *457*, 435–440. https://doi.org/10.1038/nature07675

Talke, S. A., & Jay, D. A. (2020). Changing tides: The role of natural and anthropogenic factors. *Annual Review of Marine Science*, *12*(1), 121–151. https://doi.org/10.1146/annurev-marine-010419-010727

Talke, S. A., Orton, P., & Jay, D. A. (2014). Increasing storm tides in New York harbor, 1844–2013. *Geophysical Research Letters*, *41*, 3149–3155. https://doi.org/10.1002/2014GL059574

Visbeck, M. H., Hurrell, J. W., Polvani, L., & Cullen, H. M. (2001). The North Atlantic Oscillation: Past, present, and future academy of sciences section: U.S. Frontiers of science symposium. *Proceedings of the National Academy of Sciences*, *98*(23), 12876–12877. https://doi.org/10.1073/pnas.231391598

Wahl, T., & Chambers, D. P. (2016). Climate controls multidecadal variability in U.S. extreme sea level records. *Journal of Geophysical Research: Oceans*, *121*, 1274–1290. https://doi.org/10.1002/2015JC011057

Woodworth, P. L., Hunter, J. R., Marcos, M., Caldwell, P., Menéndez, M., & Haigh, I. (2017). Towards a global higher-frequency sea level data set. *Geoscience Data Journal*, *3*, 50–59. https://doi.org/10.1002/gdj3.42

Woodworth, P. L., & Menéndez, M. (2015). Changes in the mesoscale variability and in extreme sea levels over two decades as observed by satellite altimetry. *Journal of Geophysical Research: Oceans*, *120*, 64–77. https://doi.org/10.1002/2014JC010363

Woodworth, P. L., Menéndez, M., & Gehrels, W. R. (2011). Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*, *32*, 603–618. https://doi.org/10.1007/s10712-011-9112-8

Wöppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., & Woodworth, P. L. (2008). Tide gauge datum continuity at Brest since 1711: France's longest sea level record. *Geophysical Research Letters*, *35*, L22605. https://doi.org/10.1029/2008GL035783

Wöppelmann, G., Pouvreau, N., & Simon, B. (2006). 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

Zhang, Y., Wang, G., Li, Q., Huang, W., Liu, X., Chen, C., et al. (2021). Vulnerability assessment of nearshore clam habitat subject to storm waves and surge. *Scientific Reports*, *11*(5), 569. https://doi.org/10.1038/s41598-020-80863-4