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Dynamic projections of extreme sea levels for western Europe based on ocean and wind-wave modelling

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Section S1. Impact of the wave contribution on past ESLs

The impact of the wave contribution on the past ESLs is investigated at 4 different locations by comparing return period curves of ESWL and ETWL (Fig. S1). These locations are chosen to highlight different wave regimes and processes in terms of sea level, and they also correspond to regions where the model has shown good performances compared to tide gauge data (Fig. 3). The wave regimes are described in Sect. 2.2 and Figure 1. Location (a) in Scotland is subject to low-energy swells and a mesotidal tidal regime. Location (b) in the North Sea has a mesotidal regime and is exposed to strong winds resulting in a wind wave dominated area where large storm surges occur. Location (c) along the Atlantic coast in Brittany is a macrotidal environment with energetic swells as shown on the map in Fig. 3. Finally, location (d) in the Mediterranean Sea is a microtidal environment with a tidal range that rarely exceeds 50 cm. This location is sheltered from swell and locally generated wind waves predominate.

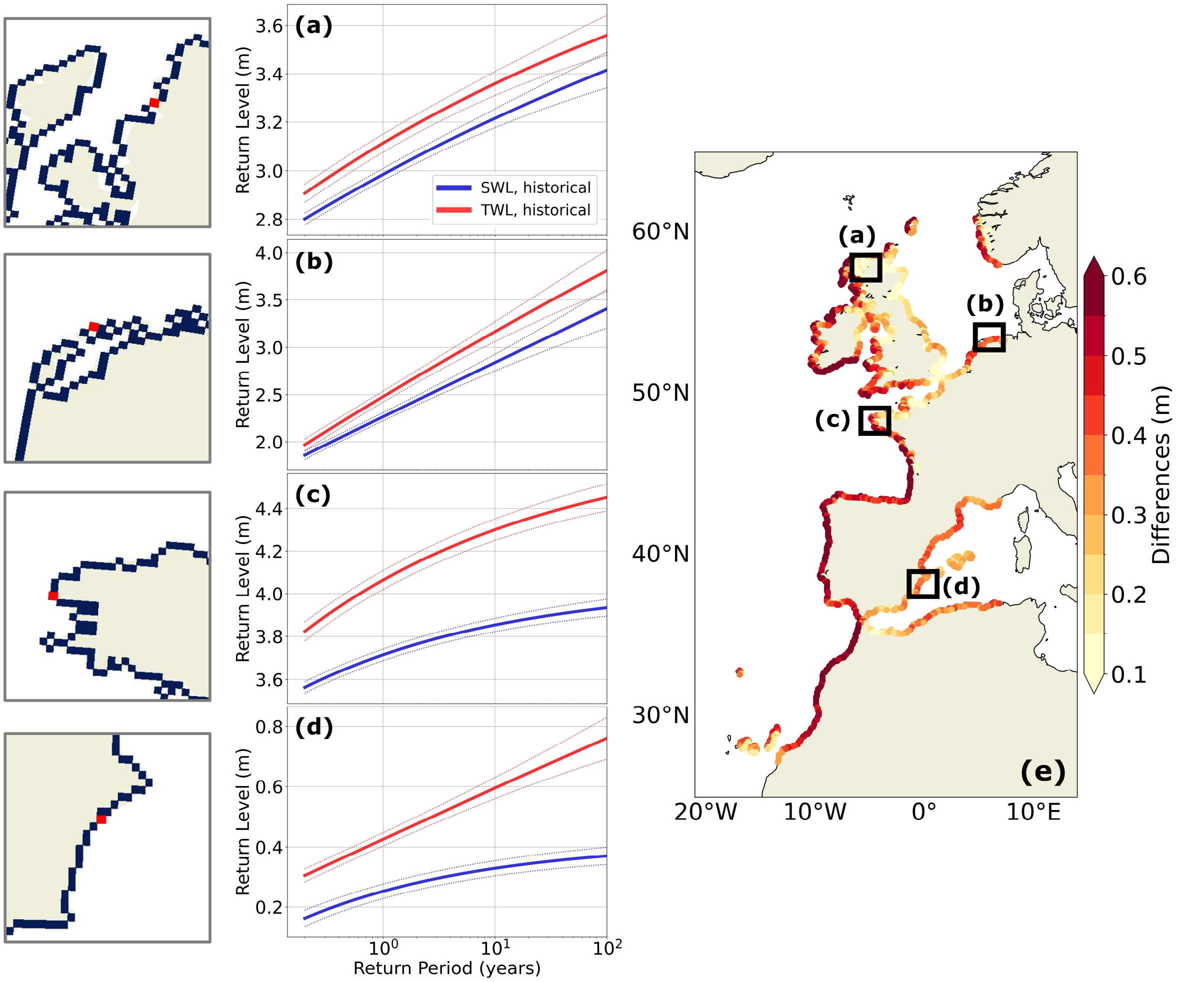

Figure S1: Return period curves for ESWL (blue) and ETWL (red) computed over 1995-2014 at 4 different locations marked on the map on the right (a) the Scottish coasts (b) the southern North Sea coasts (c) the Brittany coasts in France (d) the western Mediterranean coasts. Note the different y-axes for the different panels. The 4 thumbnails on the left highlight in red the selected coastal points in the regional ocean simulations corresponding to a horizontal resolution of about 10 km. (e) Differences between the 1-in-10-year return level of ETWL and ESWL over the 1995-2014 past period and the locations of the 4 coastal areas selected for the analyses. Here and in the following figures, the dotted lines are the 95% confidence intervals associated with the extreme value analysis method applied to compute the ESLs.

In terms of allowances (Sect. 2.5), as the wave contribution is a positive variable, the ETWLs are always higher (i.e., larger location parameter) than the ESWLs. The 1-in-10-year past return level shown in Figure 2a is up to 10 to 55 cm larger when the wave contribution is included (Fig. S1e). In the Mediterranean Sea, the impact of including the wave contribution is very substantial because the ESWLs are usually very low due to the microtidal regime (Fig. S1d). However, these results are strongly dependent on the parameterization used to compute the wave contribution (Sect. 2.3, eq (2)), as discussed in Sect. 5 and in Sect. S2.

Along the Scottish coasts and North Sea (Fig. S1a, b), the inclusion of the wave contribution only results in a shift of the curve upwards (increase in the location parameter, Sect. 2.4). More interestingly, in Brittany and in the Mediterranean Sea (Fig. S1c, d), the inclusion of wave contribution is more important since, in addition to an upward shift of the curve (larger location parameter), it increases the variability of the extremes (larger slope i.e., larger scale parameter). From a physical point of view, this means that the inclusion of the wave contribution leads to less regular extremes, because extremes in waves and other sea level components do not occur at the same time. In Brittany (Fig. S1c), the large increase in variability is found because the zone is exposed to very energetic swells. In the Mediterranean Sea (Fig. S1d), the area is not exposed to energetic swells, but adding the variability of the wave contribution is very important since the initial variability in ESWLs is very low due to the microtidal regime. In summary, the inclusion of the wave contribution increases the allowances and reduce the variability of the extremes. Therefore, the wave contribution should be considered in ESL studies and not just in wave-dominated areas.

Section S2. Impact of the wave contribution on projected changes in ESLs

The impact of the wave contribution on the future ESLs is investigated in terms of amplifications by comparing future ESWLs and ETWLs (Fig. S2). Over almost the entire domain, when the wave contribution is included, the amplifications of the historical centennial event (HCE) are smaller (Fig. S2b), and it takes longer for the HCE to become an annual event (Fig. S2c). Our results are consistent with those of Lambert et al., 2020 who showed that the addition of the wave contribution to tide gauge data was resulting in a lengthening of the amplifications timescales. Amplifications of the HCE are overestimated by up to 30 years along the Atlantic and Mediterranean coasts when the wave contribution is not accounted for.

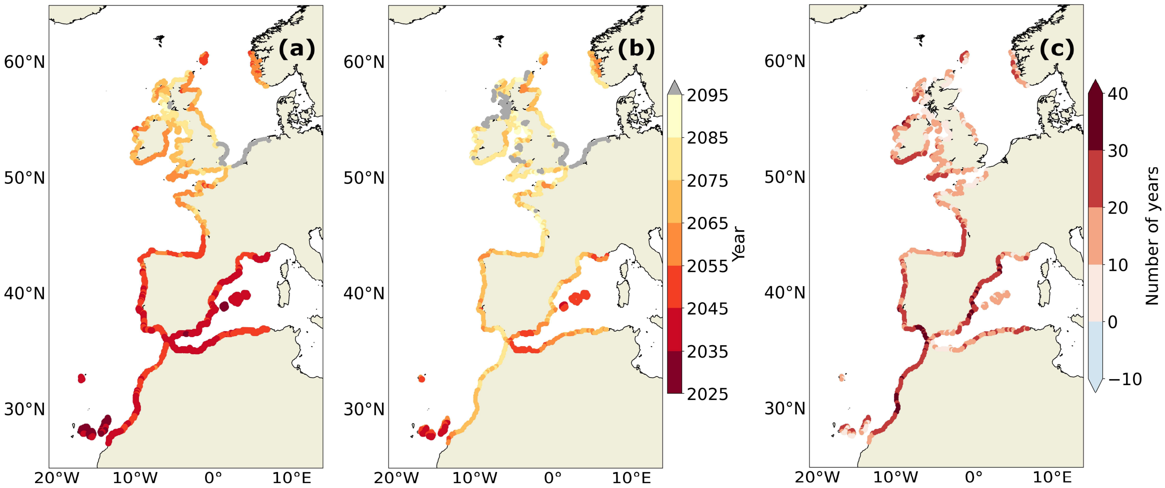

Figure S2: (a) Year in which the HCE will occur once a year in the future under the SSP5-8.5 scenario for the ESWL. (b) same for the ETWL. (c) Differences between (b) and (a). The grey dots indicate the locations where HCEs recur annually after 2095.

To understand the spatial differences of the year in which the HCE will become a yearly event in projections of Figure S2, the same four sites are analyzed (Fig. S3). For the ESWL (blue curves), the south of the domain, particularly the Mediterranean Sea, are subject to very regular ESWLs (flat curves) so that the slightest increase in sea level rise results in large amplifications (Fig. S3d). In the North Sea, the very small amplifications are due to a strong variability in ESWLs related to large storm surges (Fig. S3a). For the ETWL (red curves), the inclusion of the wave contribution results in larger extremes in projections, with almost similar characteristics as shown for the past period. In terms of amplifications, the inclusion of the wave contribution has a substantial impact mainly in Brittany and in the Mediterranean Sea (Fig. S3g,h) where the increase in the variability of the extremes over the past period are the largest (Fig. S2c,d). In Brittany and in the Mediterranean Sea, the year in which the HCE becomes annual is overestimated by 20 years (Fig. S3g) and 35 years (Fig. S3h) respectively when the wave contribution is not considered (ETWL vs ESWL). In the North Sea (Fig. S3b,f), the very high variability of the extremes due to strong storm surges leads to low amplifications in general and the HCE will not become annual by the end of the century whether for SWL or TWL, but closer to a 1-in-4-year to 1-in-8-year event. On the Scottish coast (Fig. S3a, e), almost no difference in amplification is observed between ESWL and ETWL since the wave contribution is very small.

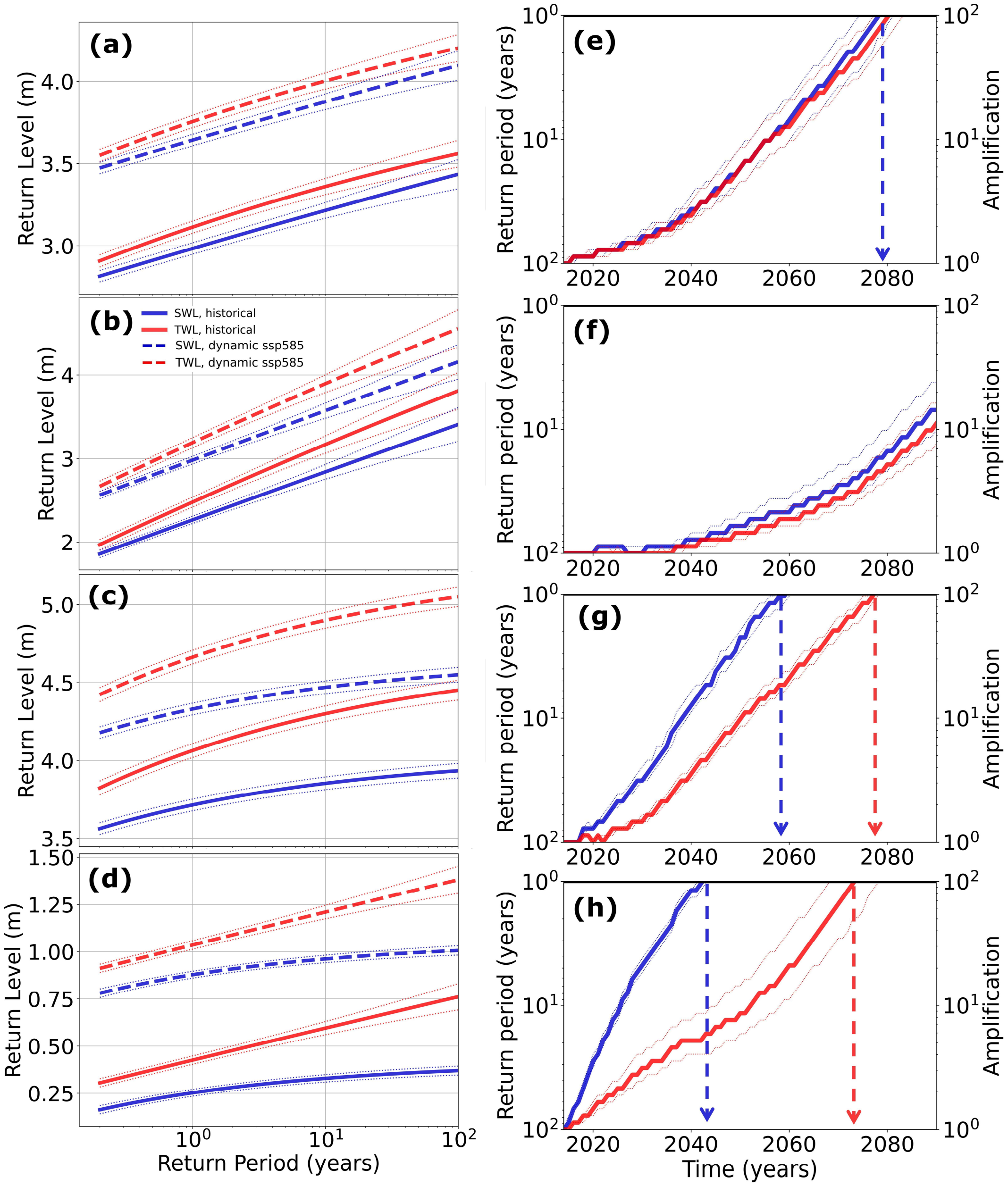

Figure S3: Left: Return period curves for ESWL (blue) and ETWL (red) over the 1995-2014 period (solid lines) and under the SSP5-8.5 scenario over the 2081-2100 period (dashed lines) at the four different locations of Figure S2: (a) the Scottish coasts (b) the southern North Sea coasts (c) the Brittany coasts in France (d) the western Mediterranean coasts. Right: Amplification of the HCE under the SSP5-8.5 scenario as a function of time for the same 4 locations for ESWL (blue) and TWL (red). The arrows represent the year in which the HCE will occur once a year in the future.

Section S3. Influence of the parameterization used to compute the wave contribution

The parameterization used to compute the wave contribution (Sect. 2.4, eq (2)) depends on the beach slope which is taken constant equal to 0.04 (4%) in space and time in the present study. Limitations associated with this method are described in Sect. 5. In Figure S4 and S5, we assess how the results found are dependent on this parameterization and more specifically on the beach slope. Several sensitivity tests were performed for slopes ranging from 0.02 (small value) to 0.1 (high value).

The influence of the beach slope on the amplifications (Fig. S2) is investigating using with beach slopes of 2 % (small value) and 10 % (high value) (Fig. S4). The differences are very large since over a large part of the Atlantic and Mediterranean domain, the year for which the HCE becomes annual differs by 50 years or more. Since in these areas the slope has a strong impact, it will be interesting to use beach slopes observed at the European regional scale when they become available. Around the UK, the impact of the choice of the beach slope is less important, but these are also locations where the impact of accounting for the wave contribution is small (Fig. S1a and Fig. S3a).

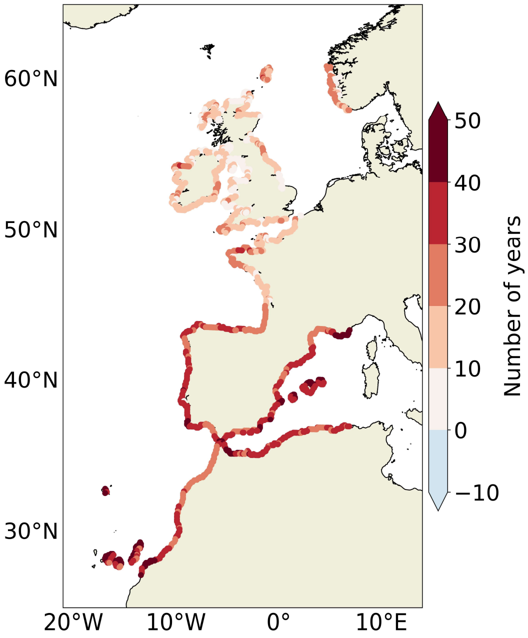

Figure S4: Difference in the year when the HCE will occur once a year in the future under the SSP5-8.5 scenario for the TWL between a beach slope of 0.1 and 0.02.

The impact of the inclusion of the dynamic changes in waves on the future ESLs as shown in Figure 7b is highlighted in Figure S5 but with beach slopes of 0.02 and 0.1. When considering the higher value of the beach slope of 0.1, i.e. larger wave contribution, the amplitude of the impact of considering dynamic changes in the wave contribution is much larger, but without significant differences because of larger uncertainties (Fig. S5b). On the contrary, with a beach slope of 2% the impact of the change in the wave contribution in the Mediterranean Sea is almost negligible (Fig. S5a), but with more significant differences. In conclusion, depending on the location, the impact of dynamic changes in waves on future ESLs can be very dependent on the parameterization used to compute the wave contribution. Thus, it may be interesting to consider future change in the wave climate for specific sites such as in the Mediterranean Sea, for instance for local studies where beach slopes information is available and of a relatively large value. However, it should be noted that even if the observed beach slope is available, this value is likely to be altered by climate change in the future, especially due to sea level rise.

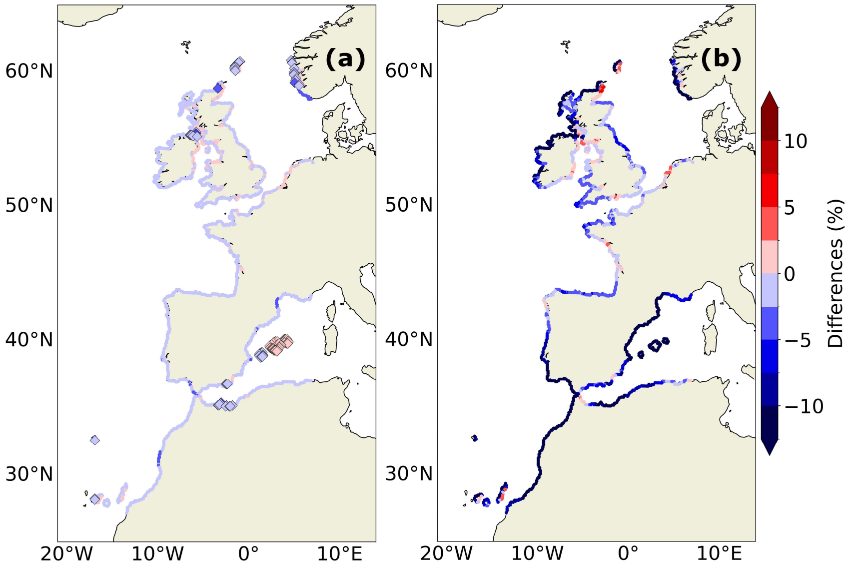

Figure S5. (a) same as Figure 6b but with a beach slope of 0.02 (2%). (b) same as Figure 6b but with a beach slope of 0.1 (10%).

Section S4. Validation and results for different return periods

In this section, the validation and results for different return levels are presented. Table S1 shows the Root Mean Squared Error (RMSE) between modeled levels and tide gauge observations. From an impact and risk assessment perspective, the 1-in-100-year return level, despite being associated with larger uncertainty and less accuracy in the models (Tab. S1), could be more relevant. However, the differences between the 1-in-100-year ESWLs and ETWLs are significantly smaller than the margin of error computed from the tide gauge estimates, which is not the case for the 1-in-10-year levels.

In our case, the overall performance improves when the wave setup is included, even if it is only roughly estimated, resulting in an RMSE up to 10 cm smaller, though there remains an underestimation of the ESLs. This is likely due to a compensatory effect between the ESL underestimation and the addition of a positive wave setup value.

Return Level	1-in-5-year level	1-in-10-year level	1-in-20-year level	1-in-50-year level	1-in-100-year level
RMSE ESWLs (m)	0.40	0.43	0.46	0.50	0.53
RMSE ETWLs (m)	0.32	0.33	0.35	0.38	0.40
Mean uncertainty of return levels for tide gauge data (m)	0.08	0.10	0.13	0.18	0.22

Table S1: Comparison of ESL return periods computed from model outputs and tide gauges over 1970-2014: RMSE (in meters), calculated as the root mean squared deviations between modeled return levels and tide gauges return levels (see locations of tide gauges in Fig 3b), for different return periods. Mean uncertainty calculated for the tide gauge data in meters calculated as the amplitude of the 95% confidence intervals for each return period.

The impact of simulating dynamic changes in extremes compared to the usually applied static approach is assessed here for the 1-in-5-year and 1-in-100-year ESWLs. The spatial pattern is quite similar between the different return levels considered with a general large increase in ESLs in the Mediterranean Sea and along Iberian coasts. More significant differences are found for the 1-in-5-year level as the uncertainties are lower, such as in the English Channel where a decrease in ESLs is found due to a decrease in the M2 mean tidal amplitude. However, the 1-in-100-year level is more commonly used in the literature for instance for adaptation purposes. In the article, the same figure is presented for the 1-in-10-year level which is a compromise between both.

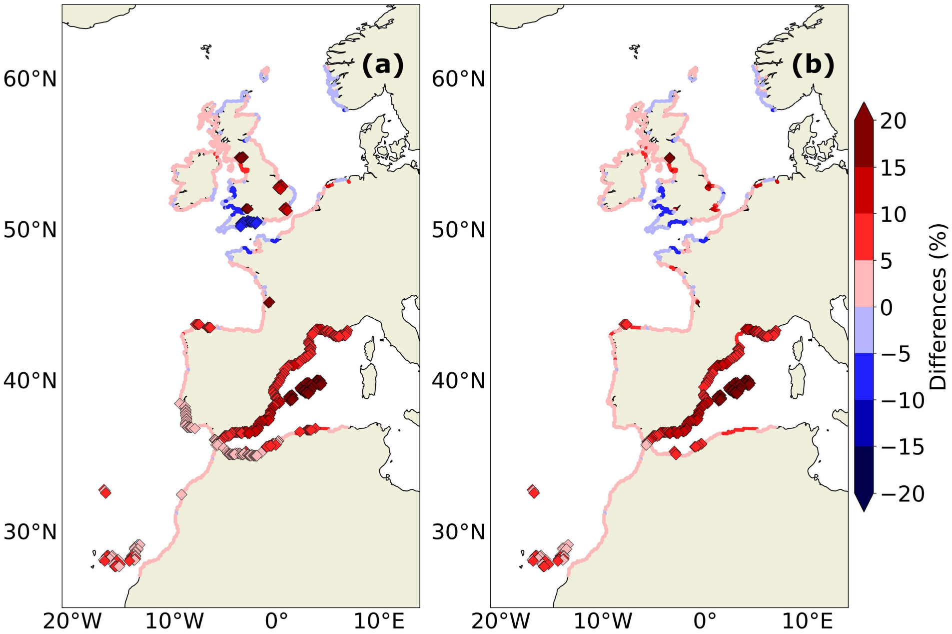

Figure S6: (a) Differences (in %) in the projected changes (2081-2100 minus 1995-2014) in the 1-in-5-year ESWLs between the dynamic and static approaches. (b) same for the 1-in-100-year ESWLs. The diamonds represent the locations where the differences are significant i.e. where the 95% confidence intervals associated with return level calculations for the static and dynamic approaches are disjoint (Fig. 2b).

Section S5. Hypothesis on the shape parameter for extreme value analyses

A reason why the projected changes in coastal drivers do not affect more the ESL projected changes could be due to the non-stationary extreme value analysis method employed. Some studies fit the SWL and TWL time series directly to non-stationary models with time-varying distribution parameters (Sect. 2.4, Robin and Ribes, 2020). We have used a simplified non-stationary approach based on the hypothesis that the shape parameter ξ is not affected by climate change (Sect. 2.4, eq (4)), which is often assumed in non-stationary studies (Marcos and Woodworth, 2017). This hypothesis may have an impact on projected changes in extremes events. To assess the error made when considering a constant shape parameter, we have performed a stationary extreme value analyses on two time periods as explained in Sect. 2.4 (time slices). Here we compare the periods 1971-2010 and 2061-2100 under the SSP5-8.5 scenario. We chose 40-year time slices as a compromise in order to obtain a long enough period to increase the confidence in the fit of the extremes and a short enough period so that the hypothesis of stationarity remains reasonable. However, the stationarity is probably violated for the end of 21st century period with the acceleration of climate change occurring under the SSP5-8.5 scenario.

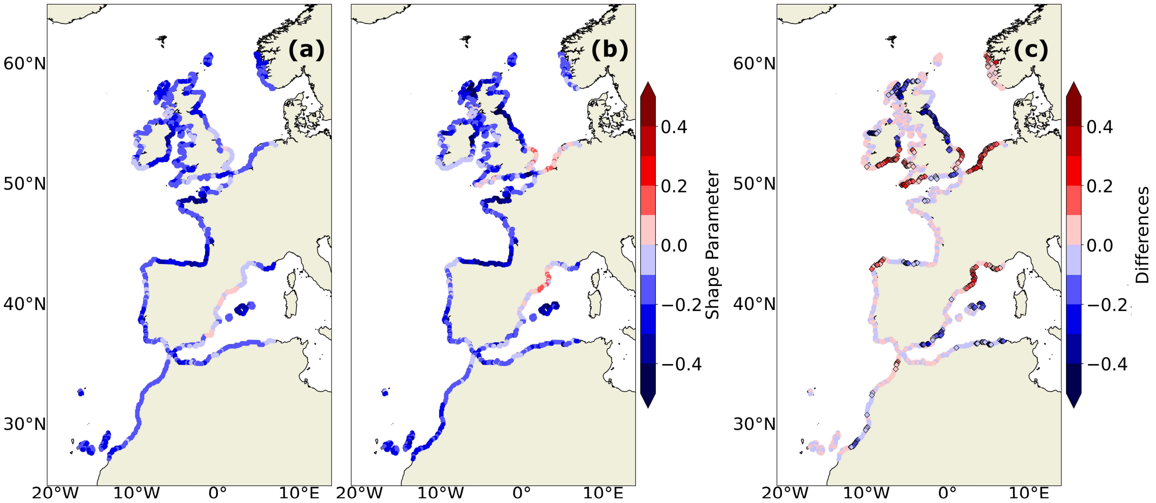

Figure S7. (a) Shape parameter ξ for the 1971-2010 time slice for the TWL. (b) Shape parameter ξ for the 2061-2100 time slice under the SSP5-8.5 scenario for the TWL. (c) Differences between (b) and (a). The diamonds represent the locations where differences in the shape parameter between the two time slices are significant i.e. where the confidence intervals associated with the calculation of the shape parameter are disjoint.

Figure S7 compares the shape parameter obtained with the two time slices for the TWL. In general, over the IBI domain, the shape parameter is negative over the 1971-2010 period (Fig. S7a) which means that the return period curves have an asymptotic limit. This could be explained by the dominance of the tides (that are very regular) on the extreme levels leading to low variability in the extremes. In projections, over the 2061-2100 period, the spatial pattern of the shape parameter seems to be well reproduced (Fig. S7b). However, some significant differences are found in the Mediterranean Sea and North Sea where the shape parameter becomes positive (return levels are unbounded). On the contrary, in the western North Sea, the shape parameter tends to decrease at the end of the century. In conclusion, based on the time slices method, the hypothesis of a constant shape parameter seems to be correct in general for the Atlantic coasts but needs to be taken with caution in specific locations such as in the North Sea. Nevertheless, the hypothesis made on the shape parameter ξ is probably not a valid reason why the projected changes in coastal drivers do not affect more the ESL projected changes.

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