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Under-estimated wave contribution to coastal sea-level rise

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SUPPLEMENTARY INFORMATION

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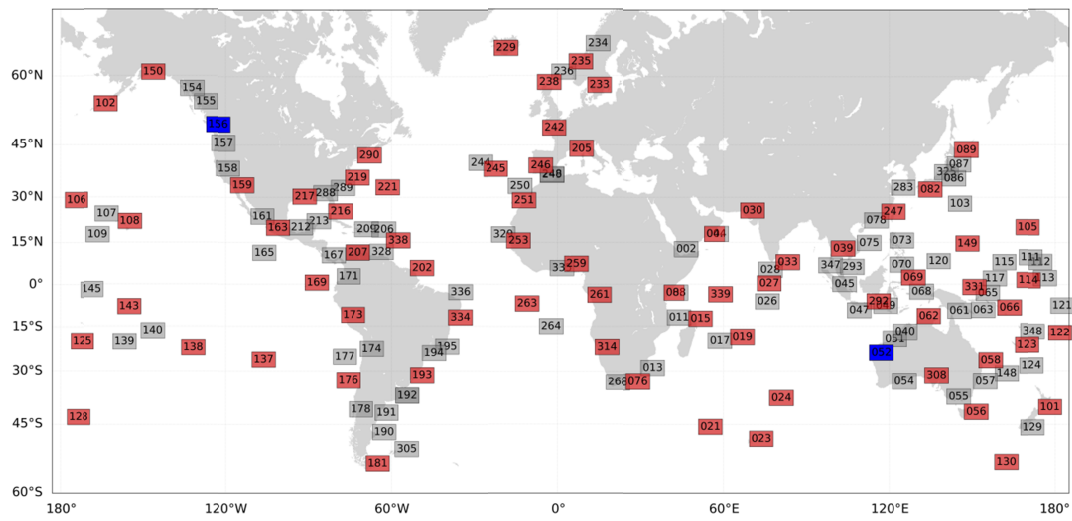
8-10 rue Hermès

31520 Ramonville Saint-Agne

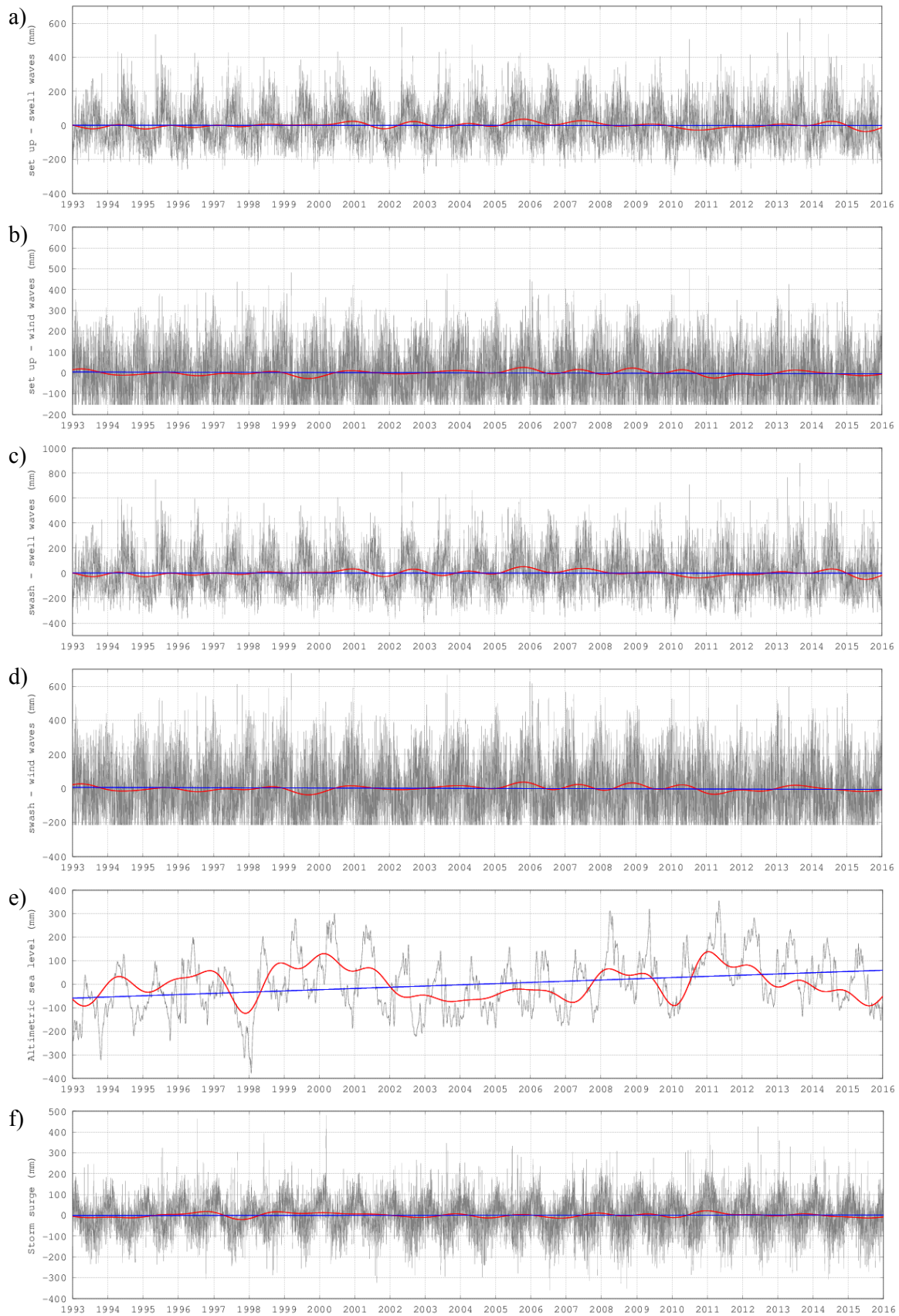
France

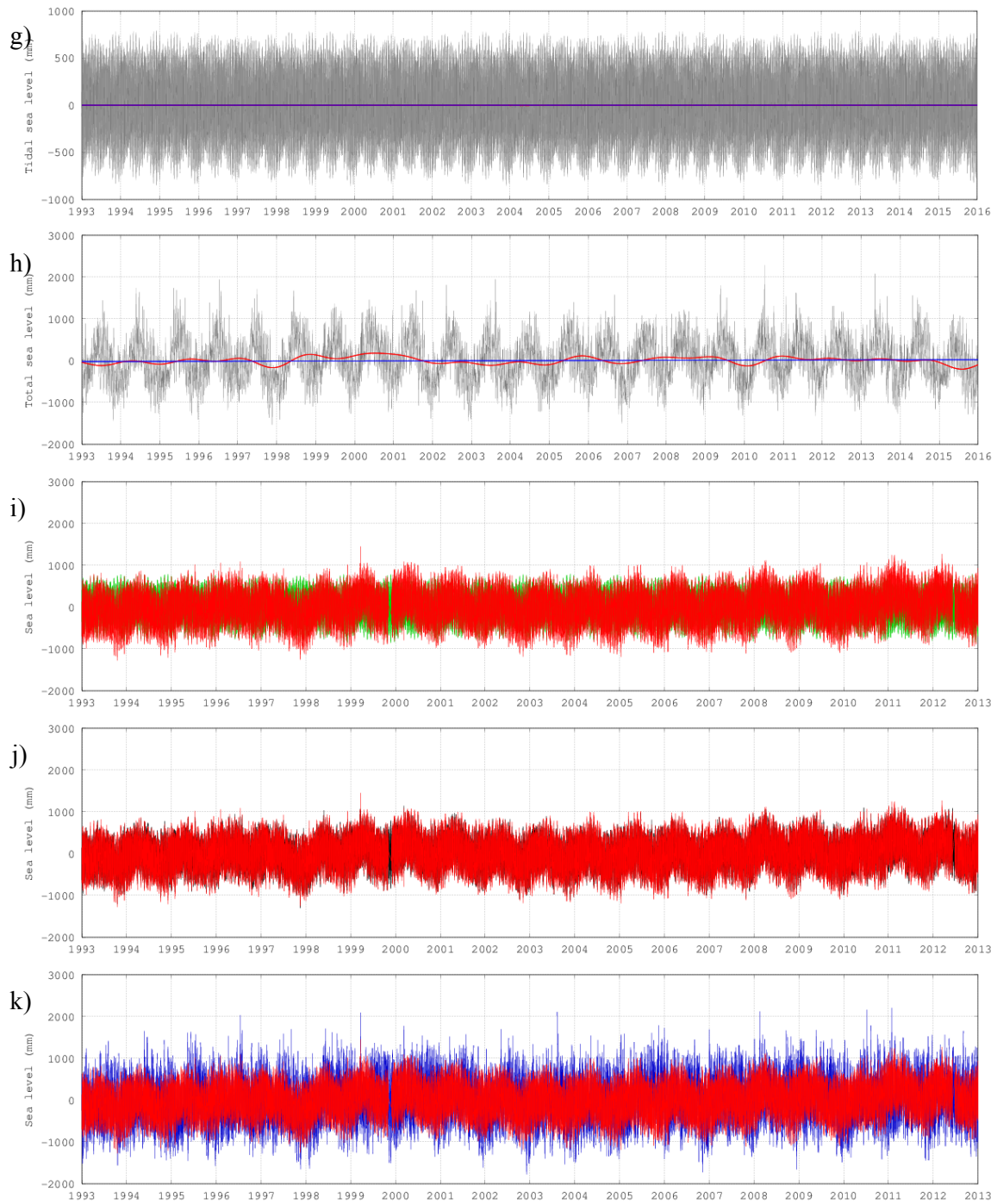
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Supplementary Information



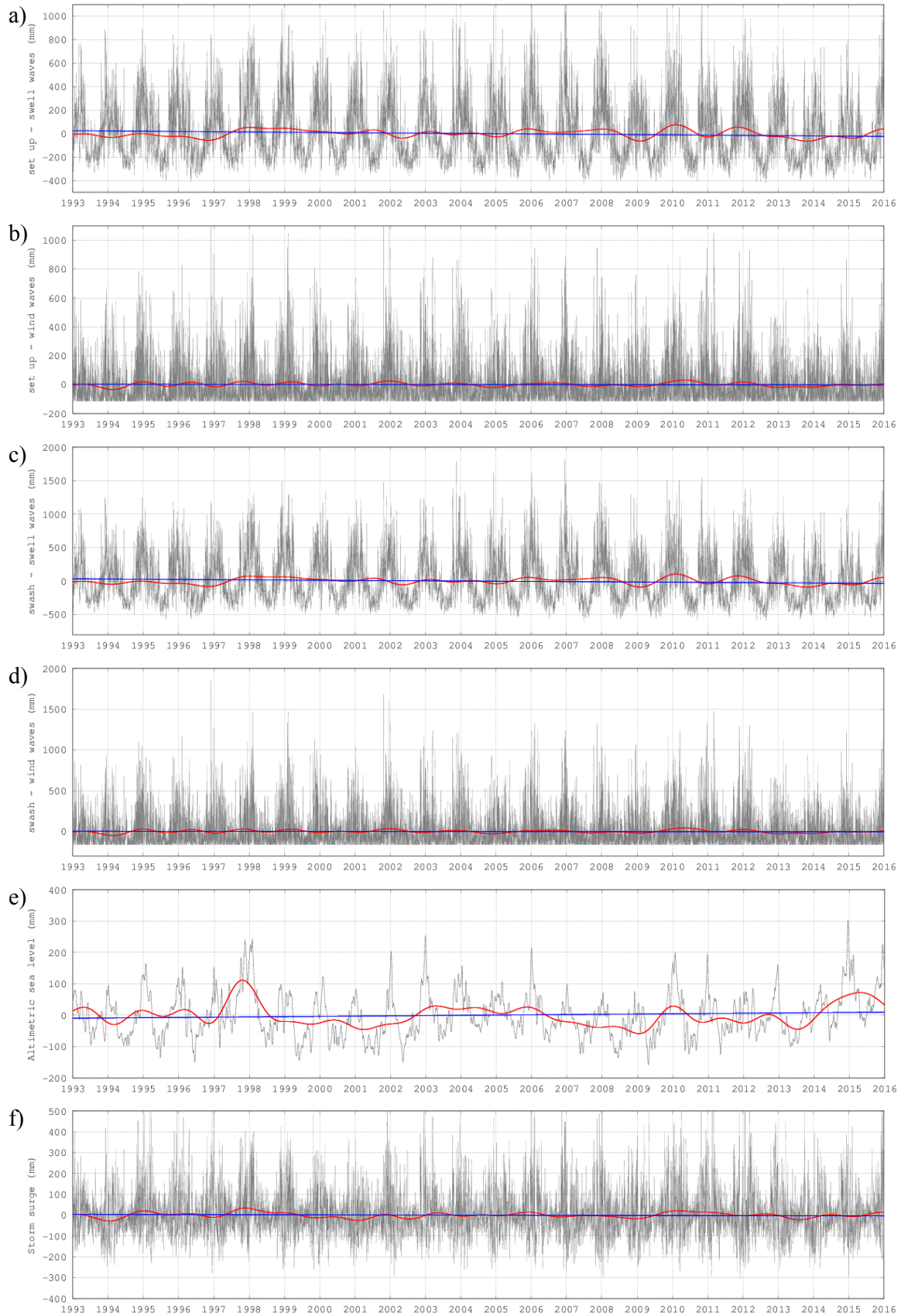
Supplementary Figure 1 | Location of the coastal sites. Coastal sites for which results are shown in the main text (Figures 2, 3, 4) are in red. Coastal sites for which time-series of the contributors to total water-level changes at the coast are provided in Supplementary Figures 2 and 3 are in blue (Carnarvon, Australia: index 052; Tofino, Canada: index 156).

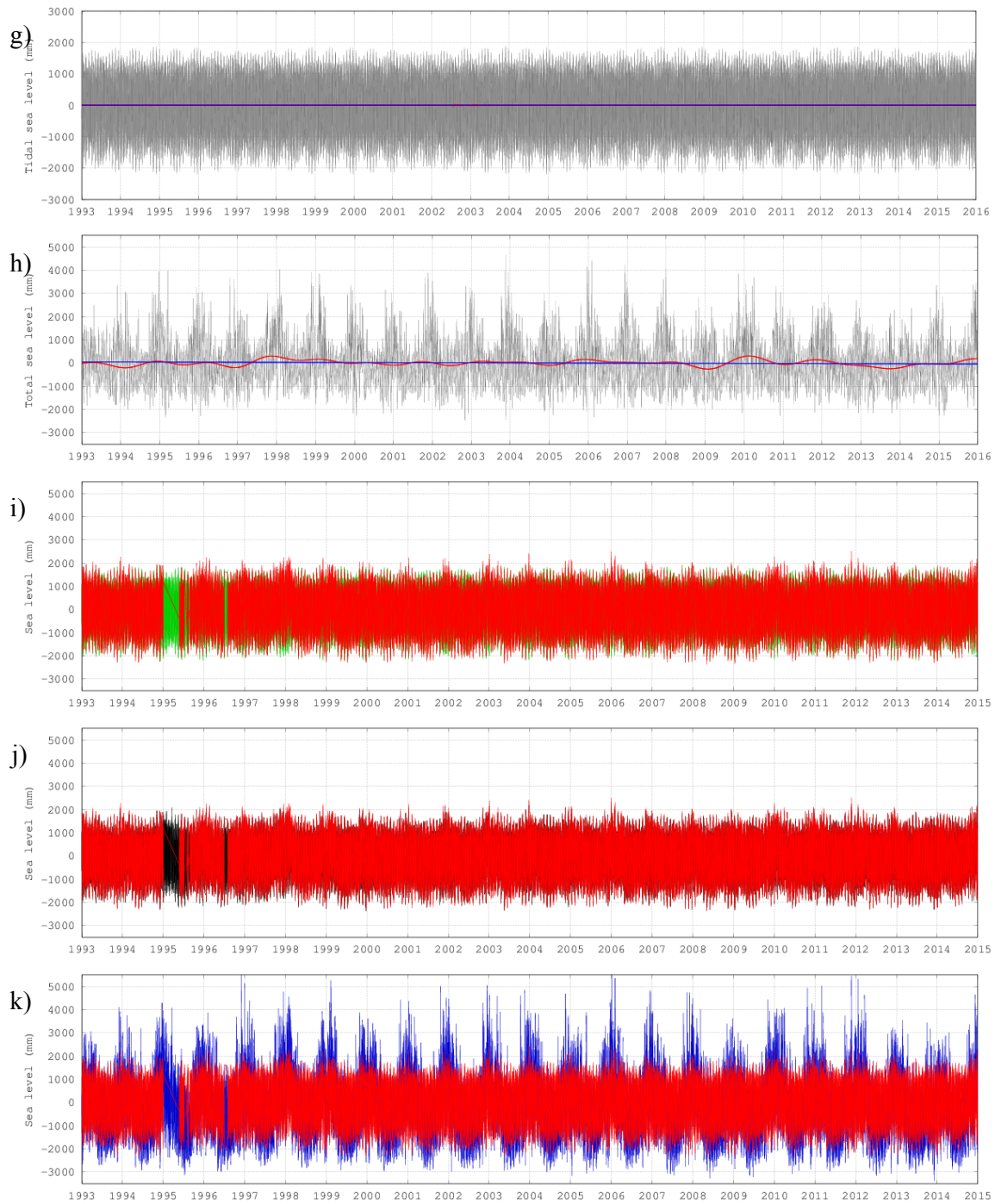




Supplementary Figure 2 | Time-series of the contributors to total water-level changes at the coast at Carnarvon (Australia, 24.90°S, 113.65°E, index 052 in Supplementary Figure 1) and comparison of water-level to the tide gauge record. Time-series of the different contributors to total water-level changes (anomalies relative to the 1993–2015 mean,

in mm): (a) swell-waves set-up, (b) wind-waves set-up, (c) swell-waves swash, (d) wind-waves swash, (e) altimetric sea level, (f) atmospheric surge, (g) tides, (h) sum of all contributors (a to g) at a daily resolution. In panels (a) to (h), the time-series is shown in grey, the linear regression (trend) in blue and the interannual variability of the detrended time-series in red. (i) to (k) Comparison to tide gauge data. The tide gauge data is shown in red. Time-series of (i) tides (in green), (j) the sum of contributors to water-level changes but excluding wave contributions (in black), (k) the sum of all contributors to water-level changes, including wave contributions (i.e. total water-level, in blue). Note the different scales for each panel.

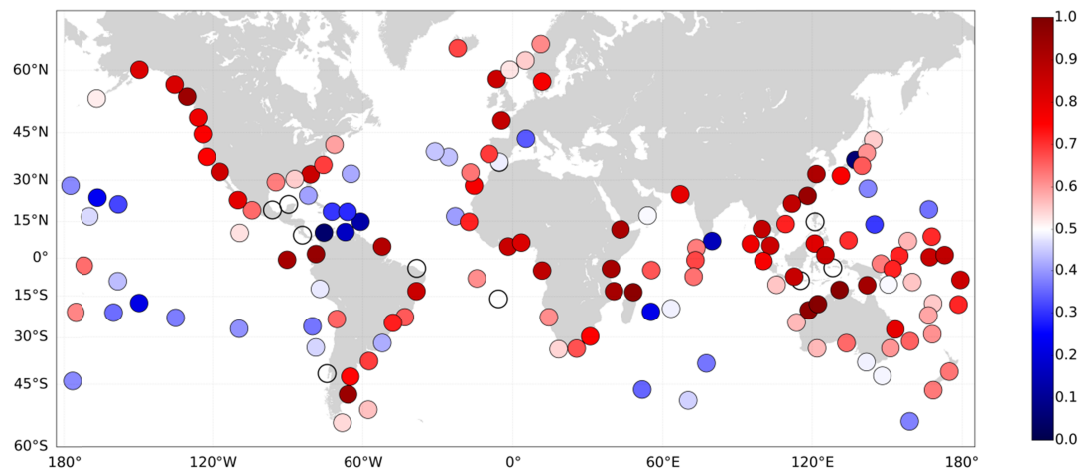




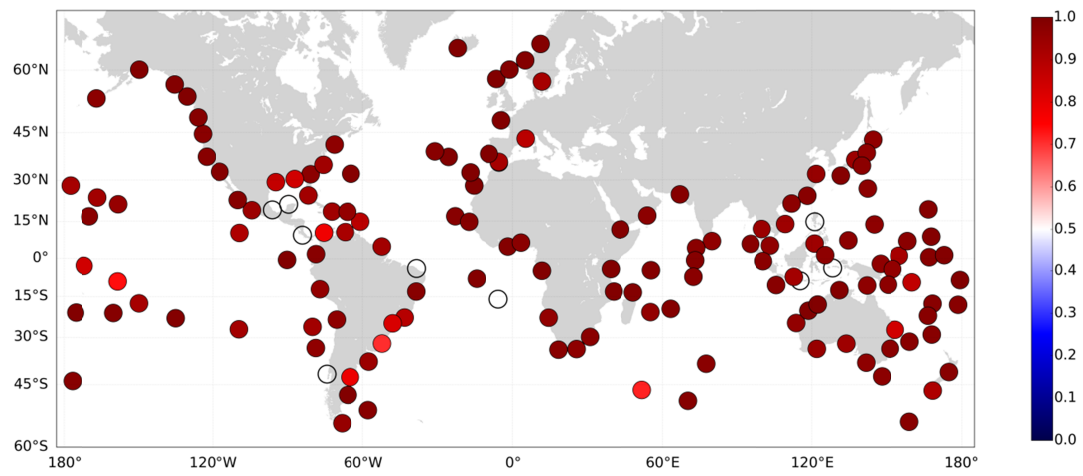
Supplementary Figure 3 | Time-series of the contributors to sea level changes at the coast at Tofino (Canada, 49.19°N 125.92°W, index 156 in Supplementary Figure 1) and comparison of sea level to the tide gauge record. (a) Time-series of the different contributors to sea level changes (anomalies relative to the 1993–2015 mean, in mm): (a)

swell-waves set-up, (b) wind-waves set-up, (c) swell-waves swash, (d) wind-waves swash, (e) altimetric sea level, (f) atmospheric surge, (g) tides, (h) sum of all contributors (a to g) at a daily resolution. In panels (a) to (h), the time-series is shown in grey, the linear regression (trend) in blue and the interannual variability of the detrended time-series in red. (i) to (k) Comparison to tide gauge data. The tide gauge data is shown in red. Time-series of (i) tides (in green), (j) the sum of contributors to sea level changes but excluding wave contributions (in black), (k) the sum of all contributors to sea level changes, including wave contributions (in blue). Note the different scales for each panel.

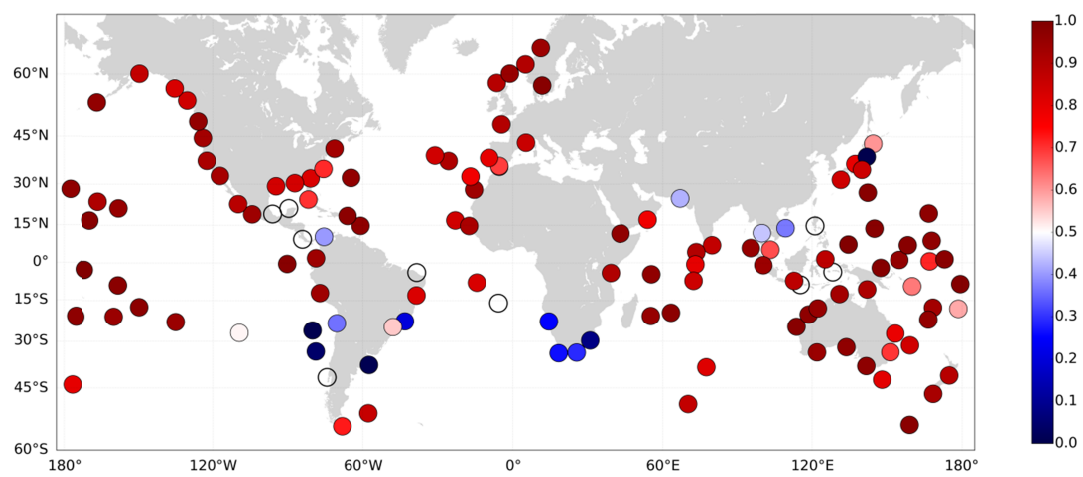
a)



b)



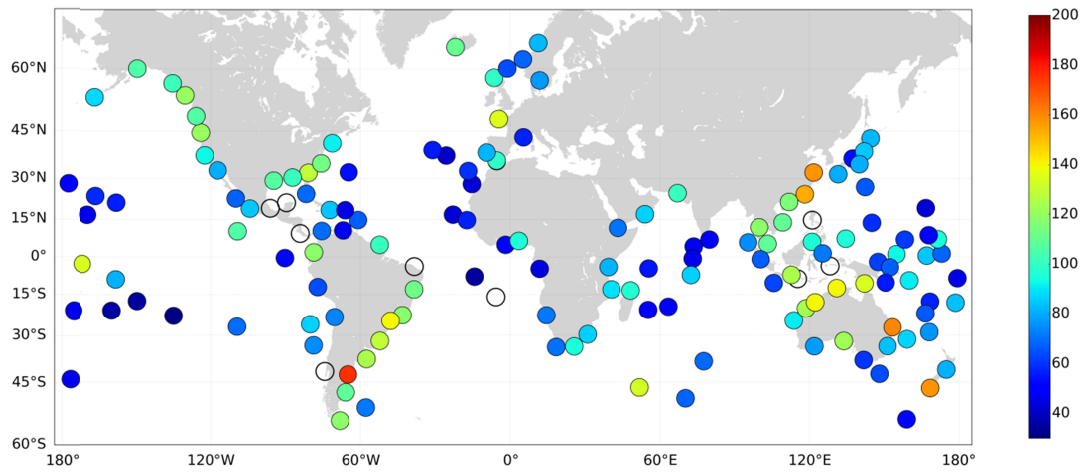
c)



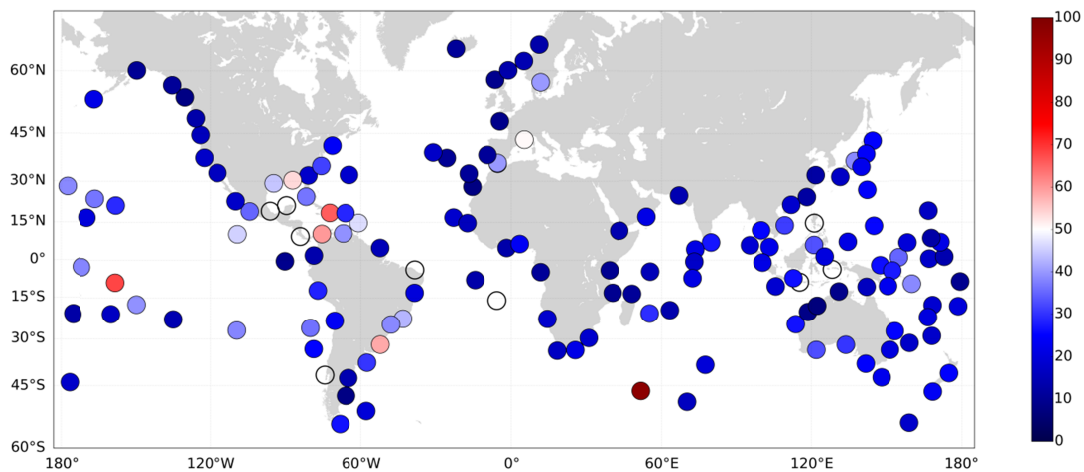
Supplementary Figure 4 | Correlation of tide gauge records with the sum of water-level contributions at the coast. (a) Estimates of water-level at the coast, including the contributions from waves (wind-wave and swell) set-up and swash (i.e. total water-level) and considering all time scales. (b) Estimates of water-level at the coast, excluding the contributions from wave set-up and swash and considering all time scales. (c) Estimates of water-level at the coast, excluding the contributions from wave set-up and swash and considering interannual-to-multidecadal time scales only.

In each panel, empty circles correspond to tide gauge records with leveling issues, so that no correlation is provided. Durations of the tide gauge records are site dependent.

a)



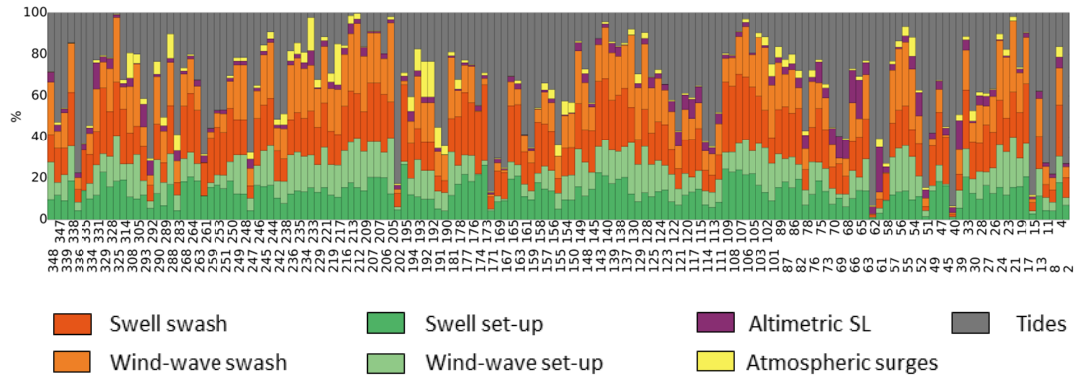
b)



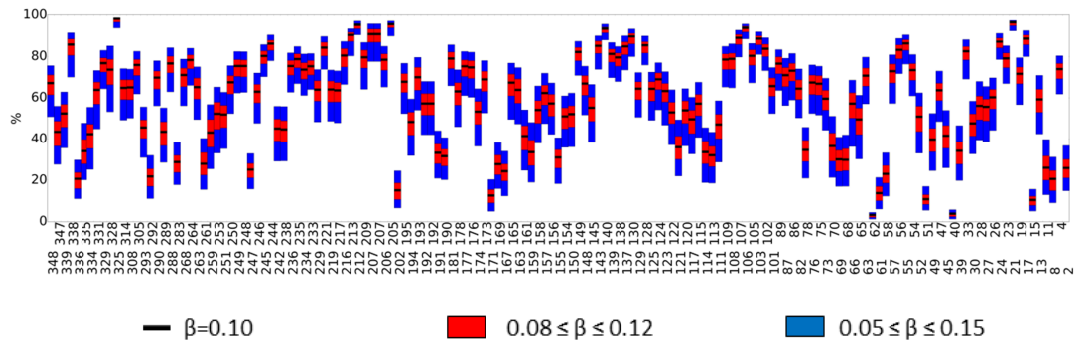
Supplementary Figure 5 | Comparison to tide gauges. (a) Root mean square of the differences between the sum of water-level contributions at the coast and tide-gauge records considering all time scales (in mm). (b) Percentage of the root mean square of the water-level estimates over the tide gauge record periods represented by the root mean square differences between the water-level estimates and the tide gauge records (shown in (a)). Estimates of water-level at the coast exclude the contributions from waves. Empty circles correspond to

tide gauge records with leveling issues, so that no value is provided. Durations of the tide gauge records are site dependent.

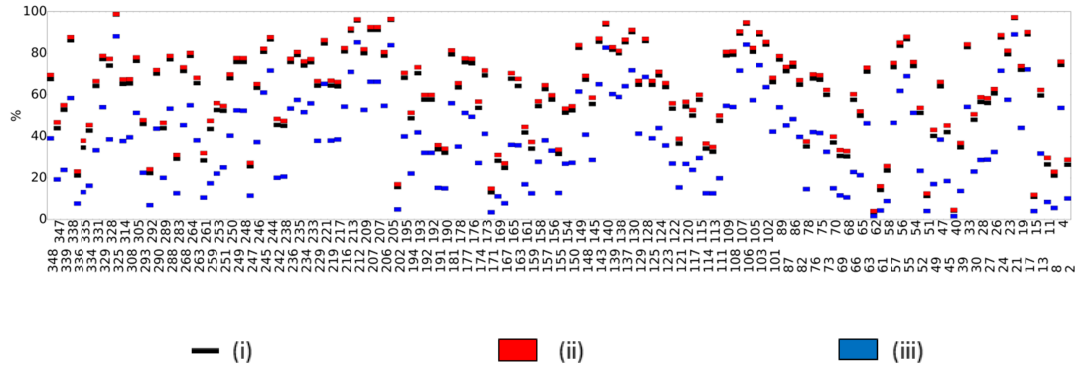
a)



b)



c)

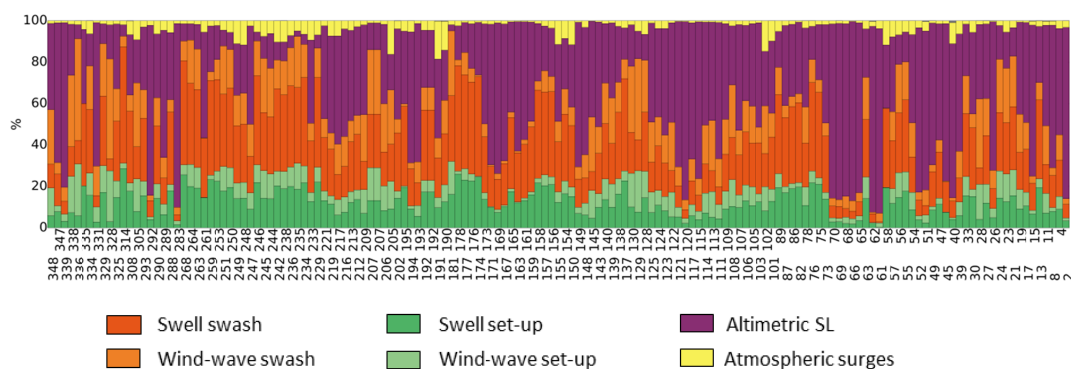


Supplementary Figure 6 | Contributions to extreme total-water levels. (a) Percentage of extreme total water-levels variance represented by each contributor at each of the 153 coastal sites (swell swash in dark orange, wind-wave swash in light orange, swell set-up in dark green, wind-wave set-up in light green, altimetry-derived sea level in violet, atmospheric surges in yellow, tides in grey). The beach slope is set to 0.1 and wave set-up and swash are

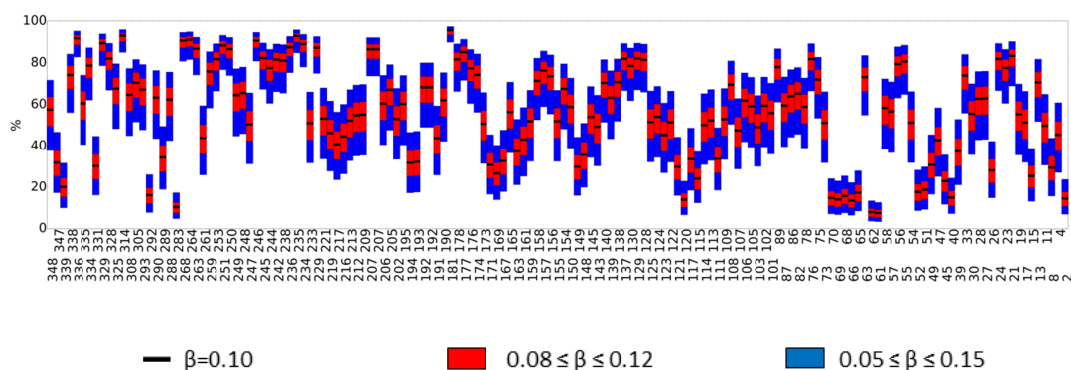
estimated with formulation (i) as in the main text. (b) Sensitivity of the percentage of extreme total water-levels variance represented by the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the beach slope parameter. The relative contribution of waves using a beach slope of 0.10 is shown in black, relative contributions of waves using beach slopes of 0.12 and 0.08 are delineated in red, relative contributions of waves using beach slopes of 0.15 and 0.05 are delineated in blue. (c) Sensitivity of the percentage of extreme total water-levels variance represented by the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the formulation used to estimate wave set-up and swash. Results for formulation (i) are shown in black, results for formulation (ii) are shown in red and results for formulation (iii) are shown in blue.

Indices on the bottom of each panel are the indices of the tide gauge records as shown in Supplementary Figure 1.

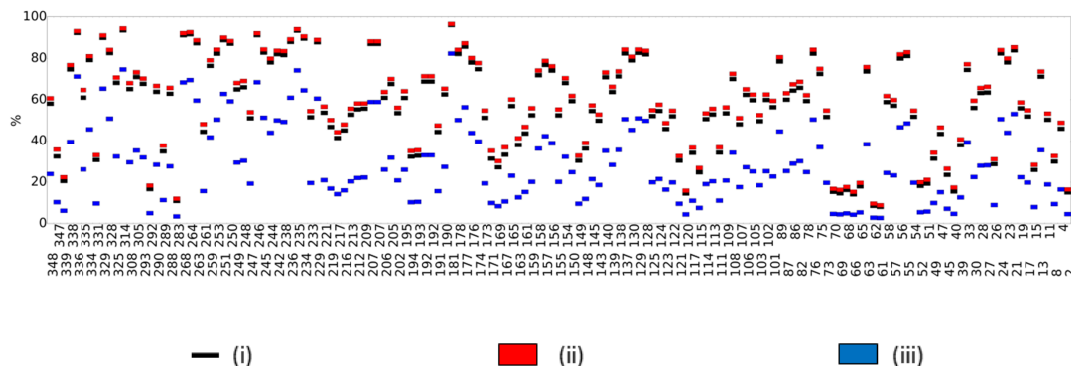
a)



b)



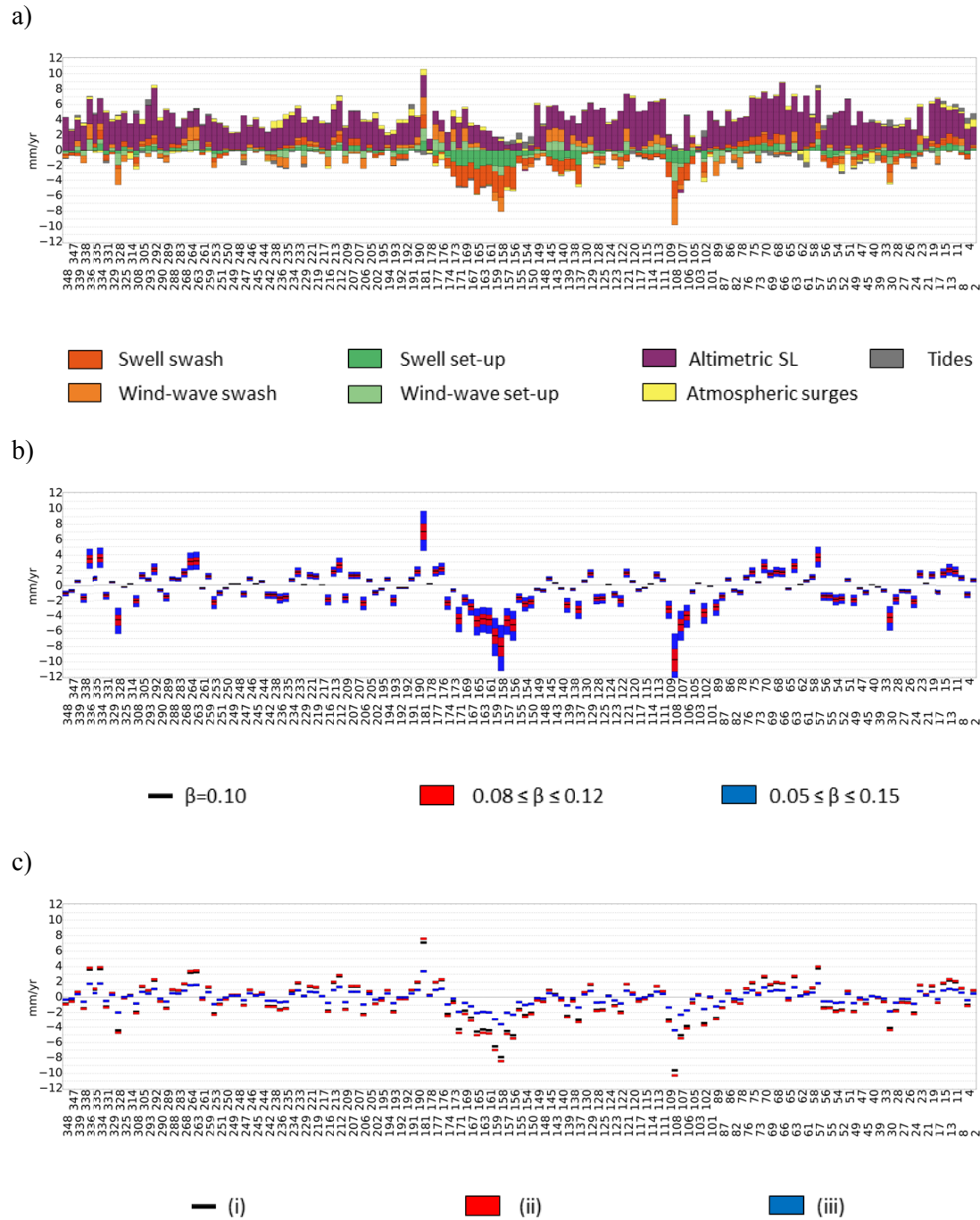
c)



Supplementary Figure 7 | Contributions to detrended interannual-to-multidecadal total-water levels. (a) Percentage of interannual-to-multidecadal total water-level variance represented by each contributor at each of the 153 coastal sites (swell swash in dark orange, wind-wave swash in light orange, swell set-up in dark green, wind-wave set-up in light green, altimetry-derived sea level in violet, atmospheric surges in yellow). The beach slope is set to

0.1 and wave set-up and swash are estimated with formulation (i) as in the main text. (b) Sensitivity of the percentage of interannual-to-multidecadal total water-level variance represented by the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the beach slope parameter. The relative contribution of waves using a beach slope of 0.10 is shown in black, relative contributions of waves using beach slopes of 0.12 and 0.08 are delineated in red, relative contributions of waves using beach slopes of 0.15 and 0.05 are delineated in blue. (c) Sensitivity of the percentage of interannual-to-multidecadal total water-level variance represented by the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the formulation used to estimate wave set-up and swash. Results for formulation (i) are shown in black, results for formulation (ii) are shown in red and results for formulation (iii) are shown in blue.

Indices on the bottom of each panel are the indices of the tide gauge records as shown in Supplementary Figure 1.

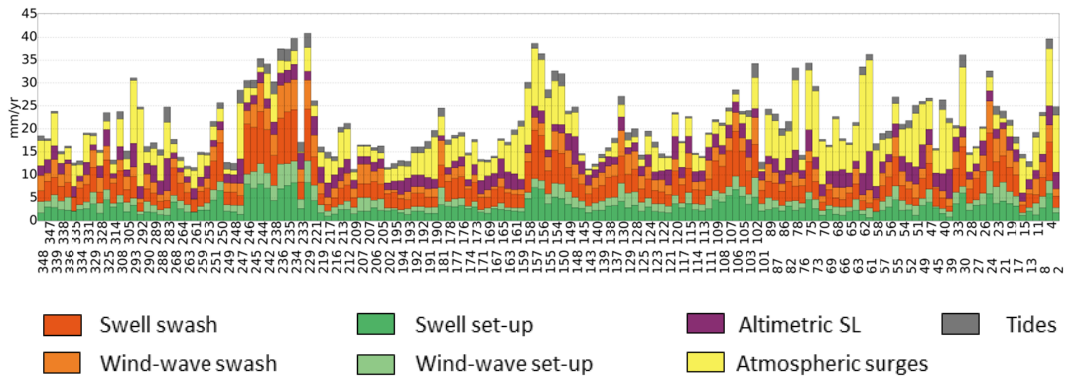


Supplementary Figure 8 | Contributions to total-water level trends. (a) Trends of each contributor to total water-levels at each of the 153 coastal sites (swell swash in dark orange, wind-wave swash in light orange, swell set-up in dark green, wind-wave set-up in light green, altimetry-derived sea level in violet, atmospheric surges in yellow, tides in grey). The beach slope is set to 0.1 and wave set-up and swash are estimated with formulation (i) as in the main

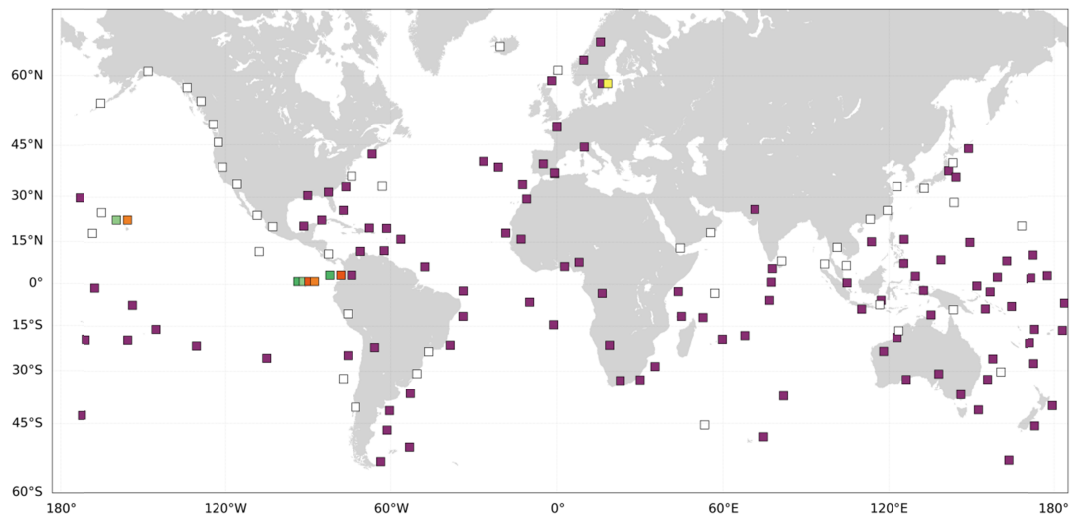
text. (b) Sensitivity of trends of the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the beach slope parameter. Trends of the wave contribution using a beach slope of 0.10 is shown in black, trends of the wave contribution using beach slopes of 0.12 and 0.08 are delineated in red, trends of the wave contribution using beach slopes of 0.15 and 0.05 are delineated in blue. (c) Sensitivity of trends of the sum of wave contributions (sum of swell and wind-wave set-up and swash) to the formulation used to estimate wave set-up and swash. Results for formulation (i) are shown in black, results for formulation (ii) are shown in red and results for formulation (iii) are shown in blue.

Indices on the bottom of each panel are the indices of the tide gauge records as shown in Supplementary Figure 1.

a)



b)



Supplementary Figure 9 | Significance of the trends relative to trends that could arise from natural climate interannual variability only. (a) 95% confidence level of trends induced by natural variability (random fluctuations with red noise modelled with an order 2 auto-regressive process to take into account the autocorrelation in time series) at interannual time-scales for each contributor to total water-level trends at the coast (swell swash in dark orange, wind-wave swash in light orange, swell set-up in dark green, wind-wave set-up in light green, altimetry-derived sea level in violet, atmospheric surges in yellow, tides in grey). (b) Contributors for which the trend (shown in Figure 4) is larger (in absolute value) than the 95% confidence level trend induced by natural interannual variability (panel a) are shown in

color for each site: swell swash in dark orange, wind-wave swash in light orange, swell set-up in dark green, wind-wave set-up in light green, altimetry-derived sea level in violet, atmospheric surges in yellow. Sites with a white box are sites for which none of the contributors to total water-level trend at the coast has a significant trend at the 95% confidence level.

Supplementary Note | Contributions to extreme events.

Our estimated contributions to extreme events are overall dominated by waves and tides (Figure 2, Supplementary Figure 6), which is consistent with previous studies. Although not accounted for in most global studies focused on extreme events, swash is the dominant contributor to total water-level extreme along open coasts located close to our network of tide gauges. Wave set-up also shows a large contribution. Regional patterns arise regarding the relative importance of the different contributions: extreme events are of highest amplitude and mostly due to both wind-waves and swells at mid-to-high latitudes (Europe, Northern America, Japan, Southern Ocean, and southern South America) (Figure 2). These regions correspond to coasts exposed to storms, high local winds and wave heights. In the tropics, extreme events have lower amplitudes, but are still a threat for the coastal population as the relative departure during extremes from usual conditions (e.g. variations below the 98% percentile) is of similar amplitude in the tropics and at higher latitudes (not shown). Wave contributions to extreme events in the tropics tend to be smaller than at mid-to-high latitudes and tides have a more dominant role, meaning that extreme levels primarily occur during spring tides. Components measured by satellite altimetry (Figure 1) have a non-negligible contribution to extreme events in the western tropical Pacific, while the contribution from atmospheric surges is significant at coastal locations facing large continental shelves (e.g. Baltic and North Seas, Argentina's coast, Figure 2).