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Uncertainties and discrepancies in the representation of recent storm surges in a non-tidal semi-enclosed basin: a hindcast ensemble for the Baltic Sea

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Observational Gauge Data

As written in the main text in Section 2.2, we provide here an overview of the used gauge data of Fig. 2, see Tab. S1. The data are obtained from the European Marine Observation and Data Network (EMODnet, https://emodnet.ec.europa.eu) and the Global Extreme Sea Level Analysis (GESLA, Woodworth et al., 2016; Haigh et al., 2022).

Table S1. Overview of the gauges used in this study, their record lengths used for this study, and their locations. Gaps are defined here as gaps in the time series greater than one day. The data is obtained from the European Marine Observation and Data Network (EMODnet, https://emodnet.ec.europa.eu) and the Global Extreme Sea Level Analysis (GESLA, Woodworth et al., 2016; Haigh et al., 2022).

station	record lengths	lon / lat	number of gaps	station	record lengths	lon / lat	number of gaps
Althagen	1979-01-01 to 2019-01-01	12.42 / 54.37	1	Ballen	1991-01-16 to 2019-01-01	10.64 / 55.82	223
Barhoeft	1979-01-01 to 2019-01-01	13.03 / 54.43	None	Barseback	1982-04-26 to 2019-01-01	12.90 / 55.76	None
Degerby	1979-01-01 to 2019-01-01	20.38 / 60.03	2	Drogden	1992-03-16 to 2019-01-01	12.71 / 55.54	147
Eckernfoerde	1989-11-01 to 2019-01-01	9.84 / 54.47	3	Flensburg	1979-01-01 to 2019-01-01	9.43 / 54.79	4
Forsmark	1979-01-01 to 2019-01-01	18.21 / 60.41	None	Furuogrund	1979-01-01 to 2019-01-01	21.23 / 64.92	None
Gedser	1979-01-01 to 2019-01-01	11.93 / 54.57	None	GoteborgTorshamnen	1979-01-01 to 2019-01-01	11.79 / 57.69	None
Greifswald	1979-01-01 to 2019-01-01	13.45 / 54.09	None	Grena	1991-01-19 to 2019-01-01	10.93 / 56.41	204
Hamina	1979-01-01 to 2019-01-01	27.18 / 60.56	2	Hanko	1979-01-01 to 2019-01-01	22.98 / 59.82	2
Heiligenhafen	1989-06-01 to 2019-01-01	11.01 / 54.37	6	Helsinki	1979-01-01 to 2019-01-01	24.96 / 60.15	2
Hesnaes	1991-10-16 to 2019-01-01	12.13 / 54.82	163	Hornbaek	1979-01-01 to 2019-01-01	12.46 / 56.09	None
Juelsminde	1996-12-06 to 2019-01-01	10.02 / 55.72	192	KalixStoron	1979-01-01 to 2019-01-01	23.10 / 65.70	None
Kappeln	1991-11-01 to 2019-01-01	9.94 / 54.66	None	Kaskinen	1979-01-01 to 2019-01-01	21.21 / 62.34	3
Kemi	1979-01-01 to 2019-01-01	24.52 / 65.67	3	KielHoltenau	1979-01-01 to 2019-01-01	10.16 / 54.37	None
Klagshamn	1979-01-01 to 2019-01-01	12.89 / 55.52	None	Koserow	1979-11-01 to 2019-01-01	14.00 / 54.06	8
Kungsholmsfort	1979-01-01 to 2019-01-01	15.59 / 56.10	None	Kungsvik	1979-01-01 to 2019-01-01	11.13 / 59.00	None
LandsortNorra	2004-10-14 to 2019-01-01	17.86 / 58.77	None	Langballigau	1991-11-01 to 2019-01-01	9.65 / 54.82	None
Marviken	1979-01-01 to 2019-01-01	16.84 / 58.55	None	Neustadt	1991-11-01 to 2019-01-01	10.81 / 54.10	1
NordreRose	1992-08-31 to 2019-01-01	12.69 / 55.64	134	OlandsNorraUdde	1979-01-01 to 2019-01-01	17.10 / 57.37	None
Oskarshamn	1979-01-01 to 2019-01-01	16.48 / 57.28	None	Oulu	1979-01-01 to 2019-01-01	25.42 / 65.04	3
Parnu	1979-01-01 to 2019-01-01	24.47 / 58.38	None	Pietarsaari	1979-01-01 to 2019-01-01	22.69 / 63.71	2
Pori	1979-01-01 to 2019-01-01	21.46 / 61.59	4	Raahe	1979-01-01 to 2019-01-01	24.41 / 64.67	3
Ratan	1979-01-01 to 2019-01-01	20.90 / 63.99	None	Rauma	1979-01-01 to 2019-01-01	21.43 / 61.13	2
Ringhals	1979-01-01 to 2019-01-01	12.11 / 57.25	None	Rostock	1979-11-01 to 2019-01-01	12.15 / 54.08	1
Sassnitz	1979-01-01 to 2019-01-01	13.64 / 54.51	None	Schleswig	1991-11-01 to 2019-01-01	9.57 / 54.51	None
Simrishamn	1982-05-31 to 2019-01-01	14.36 / 55.56	None	Skagsudde	1982-05-26 to 2018-07-03	19.01 / 63.19	16
Skanor	1992-02-17 to 2019-01-01	12.83 / 55.42	None	Smogen	1979-01-01 to 2019-01-01	11.22 / 58.35	None
Spikarna	1979-01-01 to 2019-01-01	17.53 / 62.36	None	Stenungsund	1979-01-01 to 2019-01-01	11.83 / 58.09	None
Stockholm	1979-01-01 to 2019-01-01	18.08 / 59.32	None	Stralsund	1979-01-01 to 2019-01-01	13.10 / 54.32	1
Turku	1979-01-01 to 2019-01-01	22.10 / 60.43	2	Ueckermuende	1979-01-01 to 2019-01-01	14.07 / 53.75	None
Vaasa	1979-01-01 to 2019-01-01	21.57 / 63.08	2	Viken	1979-01-01 to 2019-01-01	12.58 / 56.14	None
Visby	1979-01-01 to 2019-01-01	18.28 / 57.64	None	Warnemuende	1979-01-01 to 2019-01-01	12.10 / 54.17	5
Wismar	1979-01-01 to 2019-01-01	11.46 / 53.90	3	Wolgast	1979-01-01 to 2019-01-01	13.77 / 54.04	1

Model performance

In addition to the ESL comparison in the main text, we compare here the full length time series of the tide gauge stations with the different model runs. We compare the Root Mean Square Error (RMSE),

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\eta_i^{\mathrm{obs}} - \eta_i^{\mathrm{mod}}\right)^2}, \tag{1}$$

and the Pearson correlation coefficient R,

$$R = \frac{1}{N}\sum_{i=1}^{N}\frac{(\eta_i^{\mathrm{mod}} - \bar{\eta}^{\mathrm{mod}})(\eta_i^{\mathrm{obs}} - \bar{\eta}^{\mathrm{obs}})}{\sigma^{\mathrm{mod}}\sigma^{\mathrm{obs}}}, \tag{2}$$

where η_i denotes the discrete time series of the observed sea level and the modelled sea level, respectively, $\bar{\eta}$ denotes the temporal mean of the respective time series, and σ denotes the respective standard deviation. For all simulations the correlation coefficients are all around 0.9 and most RMSEs are smaller than 0.1,m (Fig. S1). For stations in the Kattegat, the R-values are smaller since our simulations excluded tides which are still present in this area. Also for the tide gauges in coastal lagoons, e.g. Althagen, the correlation is much smaller since the sea level dynamics cannot be captured correctly due to the coarse resolution.

Return levels obtained from the GEV method

As written in the main text in Section 3.2.1, we show here the variability of the GEV return levels for each ensemble member for the station 'Warnemuende', see Fig. S2. The comparison of the observed GEV return levels with the modelled GEV return levels shows that the ESL biases are directly reflected in the return level estimates. Depending on the atmospheric forcing the increased wind speed significantly reduced the bias for this station, see Fig. 3 of the main text, which also improved the GEV fit, e.g. for the UERRA forcing. However, the GEV return levels are sometimes closer to the observations in the default wind simulations, e.g., coastDat1 and coastDat3. As expected, the ensemble mean is close to the observed gauge return levels, especially for the higher return levels and therefore the long return periods.

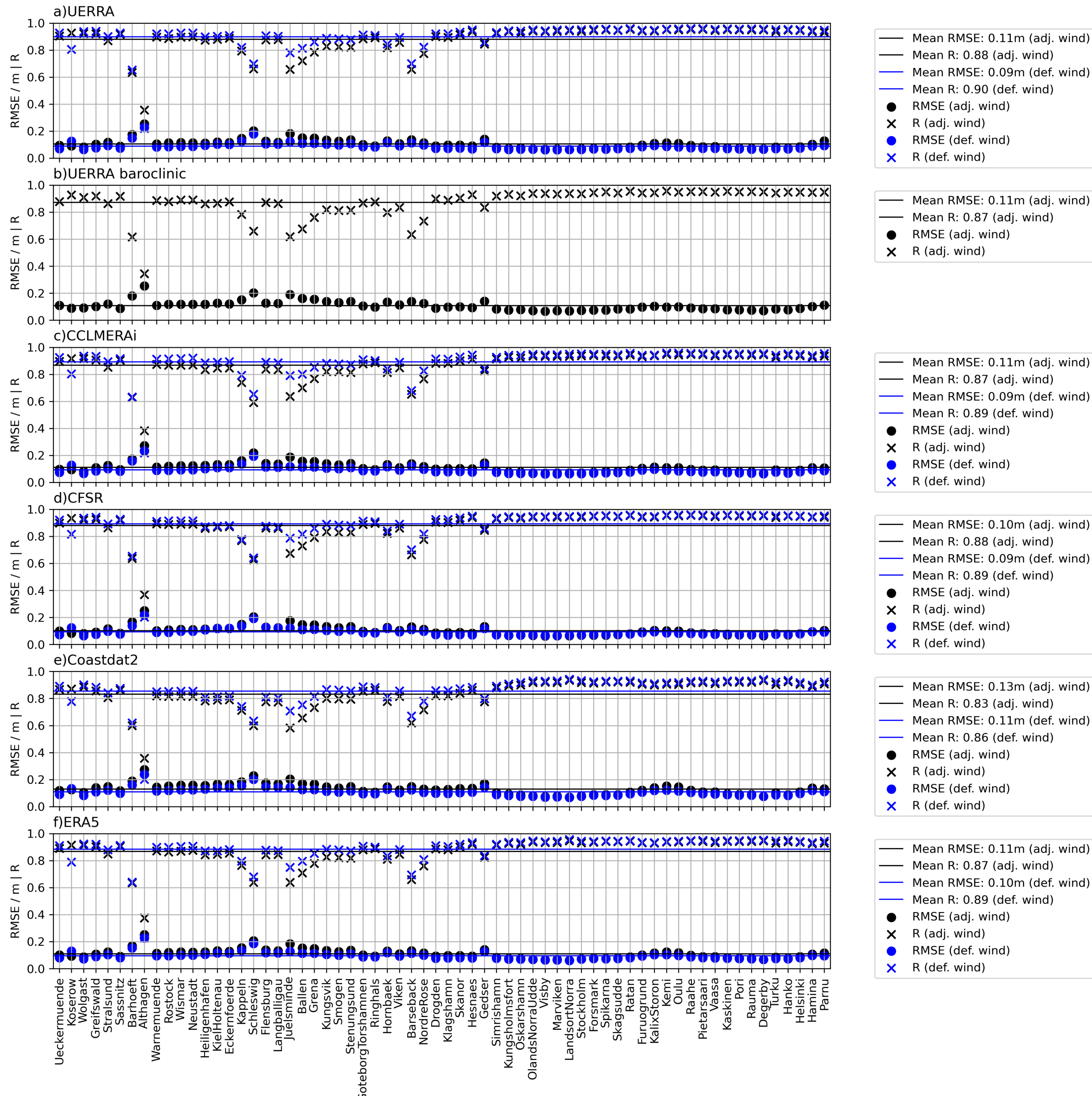

Figure S1. Comparison of the Root Mean Square Error (RMSE) and the Correlation coefficient between the different model runs for each tide gauge station. Note that the values between the adjusted wind speed simulations (black) and the default wind speed simulations (blue) are very similar. Therefore, the black dots are hidden behind the blue dots.

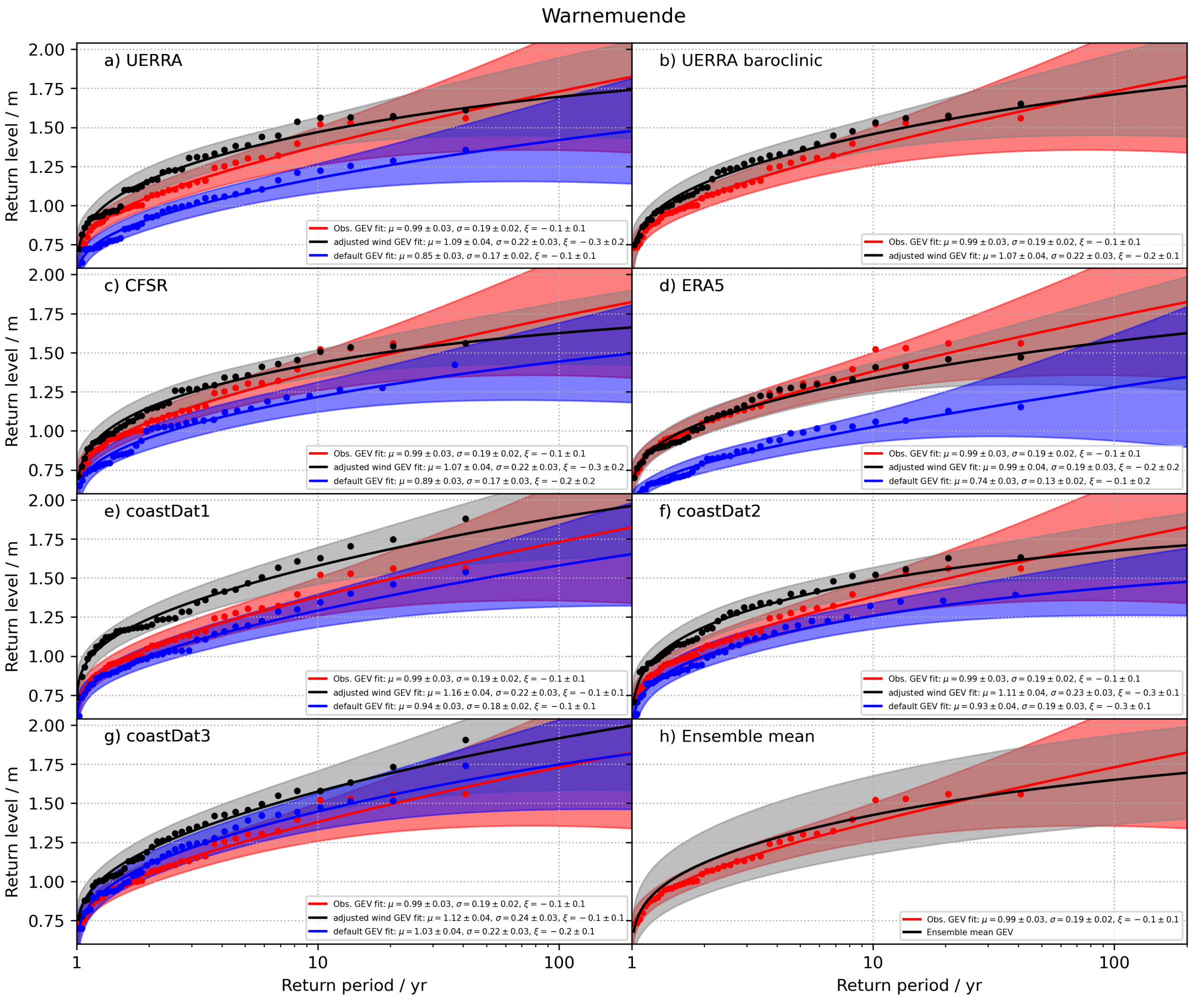

Figure S2. Comparison of the observed GEV (red, shaded red: 95 % percentiles) to the modelled GEV (black, shaded grey: 95 % percentiles) for each ensemble member. In addition, the annual maxima are scattered as dots in the respective colors. In the ensemble mean panel h) the grey shaded area marks the 95% confidence interval of the ensemble.

Return levels obtained from the GPD method

As written in the main text in Section 3.2.2, we provide the plots of the GPD return levels in Fig. S3 for the station 'Warnemuende', 30-year GPD return levels for all stations in Fig. S4, and the deviation from the ensemble mean in Fig. S5. For 'Warnemuende', the biases are similar to the GEV return levels, e.g. for UERRA, the default wind case underestimates the distribution, whereas the adjusted wind case slightly overestimates the distribution. Again, the default wind case gives better return levels for the coastDat1 and coastDat3 datasets. However, the ensemble mean gives an almost perfect agreement with the observed return levels of the GPD method. It should be noted that the return levels of the GEV method are generally higher for the high return periods compared to the GPD method. For this station, the estimated 200-year return level from the observations is 1.5 m for the GPD method and > 1.75 m for the GEV method. Regarding all stations around the Baltic Sea, the comparison of the modelled return levels to the return levels based on observations shows a similar picture than the GEV return levels, see the main text. The deviation from the ensemble mean, Fig. S5, show a similar pattern than the GEV, except slightly different values for the return levels, see also the main text.

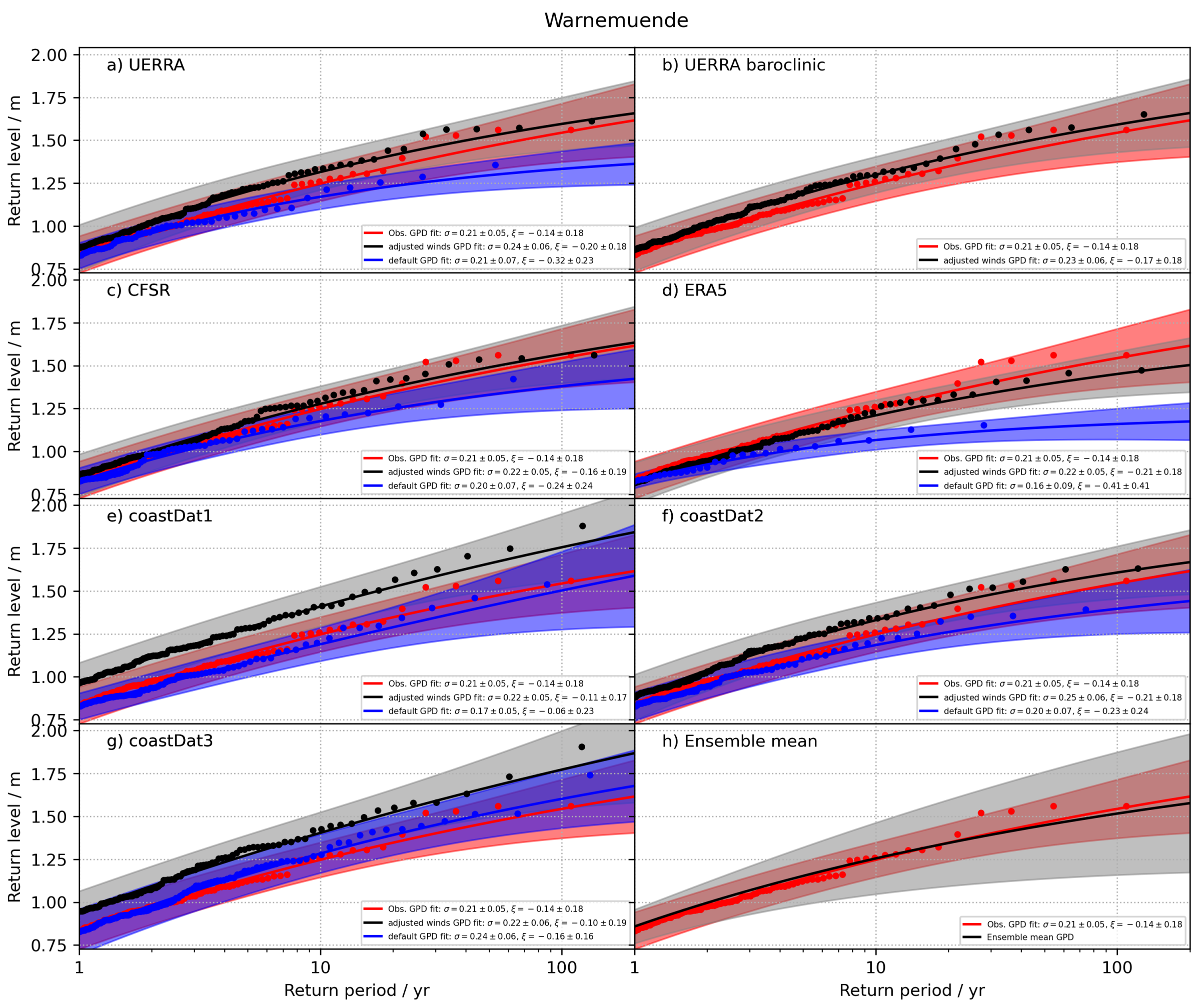

Figure S3. Comparison of the observed GPD (red, shaded red: 95 % percentiles) to the modelled GPD (black, shaded grey: 95 % percentiles) for each ensemble member. In addition, the individual ESLs found with the peak-over-threshold-method are scattered as dots in the respective colours. In the ensemble mean panel h) the grey shaded area marks the 95% confidence interval of the ensemble.

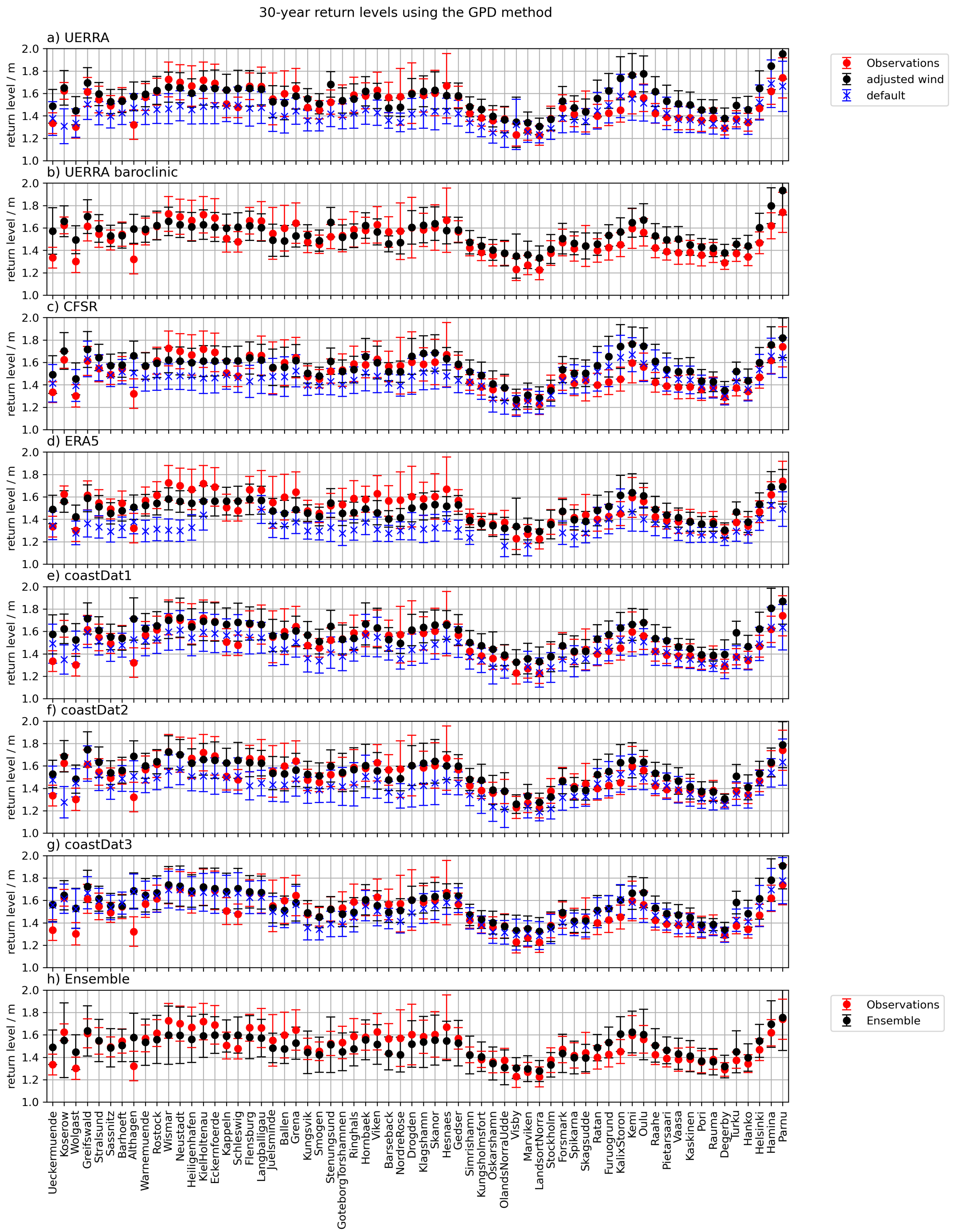

Figure S4. Summary of the 30-year return levels using the GPD method for each gauge station and each ensemble member: a)-g) return levels and 95% confidence intervals for each atmospheric forcing and each simulation. h) ensemble mean and the ensemble 95% confidence interval. The blanks denote where the GPD fit was not converging which mainly occurred for the default wind speed ERA5 simulation.

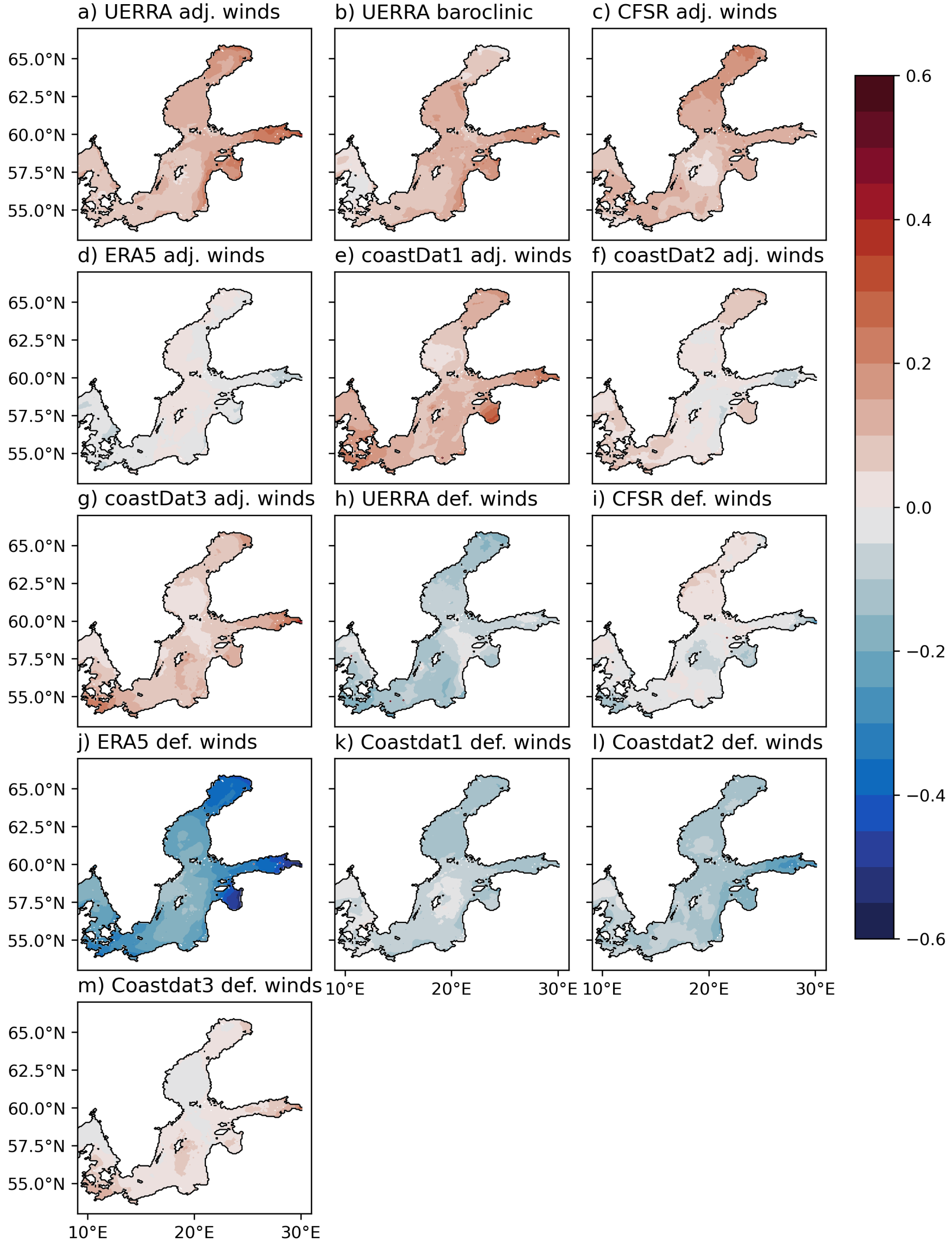

Figure S5. Spatial distribution of the 30-year GPD return level deviation from the ensemble mean (see Fig. 5c in the main text) for each ensemble member.

Table S2. Comparison of the trends of annual storm season maxima for to different time slices: 1979-2018 and 1961-2005.

station	trend 1979-2018 / mm yr^{-1}	trend 1961-2005 / mm yr^{-1}
Hornbaek	-3.35	-2.10
Klagshamn	-1.32	1.99
Flensburg	-2.09	-0.58
Furuogrund	-0.25	-0.35
Gedser	-3.37	2.26
Kungsholmsfort	0.28	1.02
Parnu	-5.92	-1.40
Ratan	-0.40	0.72
Sassnitz	-2.01	1.06
Smogen	-0.69	3.29
Stockholm	-0.94	-1.31
Warnemuende	-1.07	0.76
Wismar	-3.33	3.83

Time slice dependence of the trends

The trends we found are in the annual maximum sea levels are contradicting to the literature (e.g. Soomere and Pindsoo, 2016; Pindsoo and Soomere, 2020). Therefore, we compared the trends of the time period of the present ensemble, 1979-2018, with the time period of Pindsoo and Soomere (2020), 1961-2005. The trends are listed in Tab. S2 for stations which cover the two time periods.

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