S1 Bounds on the model part of the pass offsets

The uniform part of the SWOT minus model difference over pass p and sub-basin k is written

$$u_{pk} = a_{pk} - b_{pk}, \tag{S1}$$

where a_{pk} is the SWOT error and b_{pk} the model error uniform over the pass and sub-basin, and g_{pk} is the gauge-based model offset at the same samples. With σ_u, σ_a and σ_b the standard deviations of u_{pk}, a_{pk} and b_{pk}, the standard deviation of the model part is bounded under increasingly strong assumptions. Without any assumption on the error covariances, the triangle inequality gives

$$\sigma_b \geq \sigma_u - \sigma_a, \tag{S2}$$

and if a_{pk} and b_{pk} are independent,

$$\sigma_b \geq \left(\sigma_u^2 - \sigma_a^2\right)^{1/2}. \tag{S3}$$

In both cases σ_a is bounded by the SWOT minus gauge cRMSD at the gauge collocations, 4.73 cm, or by the SWOT error from triple collocation, 4.14 cm, which assumes that the SWOT error uniform over a pass and sub-basin is not larger than the SWOT error at a single pixel. If the errors of SWOT and of the gauges are independent of each other and of the model errors, $\mathrm{cov}(u_{pk}, -g_{pk}) = \sigma_b^2$ and the standard deviation of g_{pk} is at least σ_b, so that without any bound on σ_a

$$\sigma_b \geq |r_{ug}|\, \sigma_u, \tag{S4}$$

where r_{ug} is the correlation of u_{pk} and g_{pk}. Triple collocation of u_{pk} and g_{pk} then gives

$$\sigma_b^2 = \mathrm{cov}(u_{pk}, -g_{pk}), \qquad \sigma_a^2 = \sigma_u^2 - \mathrm{cov}(u_{pk}, -g_{pk}), \tag{S5}$$

if the model error at the gauges equals that offshore. Otherwise σ_b from Eq. (S5) describes the part of the model error that the gauges also see.

For the whole area σ_u is 6.00 cm. The bounds on σ_b are 1.26 cm from Eq. (S2), 3.68 and 4.34 cm from Eq. (S3) for the two bounds on σ_a, and 3.90 cm (3.32 to 4.41 cm) from Eq. (S4), which correspond to model shares of at least 4, 38, 52 and 42% of the variance. Equation (S5) gives $\sigma_b = 3.85$ cm (3.34 to 4.28 cm) and $\sigma_a = 4.60$ cm, a model share of 41% (36 to 46%). The intervals come from resampling 21-day blocks, because the pass offsets decorrelate within one to six days. Table S2 gives the values for each sub-basin and Fig. S5 shows them with their confidence intervals.

The bound from Eq. (S4), 3.90 cm, is slightly larger than the estimate from Eq. (S5), 3.85 cm, because the standard deviation of g_{pk}, 3.80 cm, is slightly smaller than the estimated σ_b, so that the error variance of the gauge-based offset comes out at -0.36 cm^2, close to zero. The estimate of 41% therefore describes the model error that the gauges see, whereas the bound of 52% applies to the whole model part, including model error that the gauges miss. The two figures rest on different assumptions and are not contradictory, since the first requires independent errors of SWOT, the gauges and the model, and the second requires in addition that the SWOT error uniform over a pass is not larger than at a single pixel.

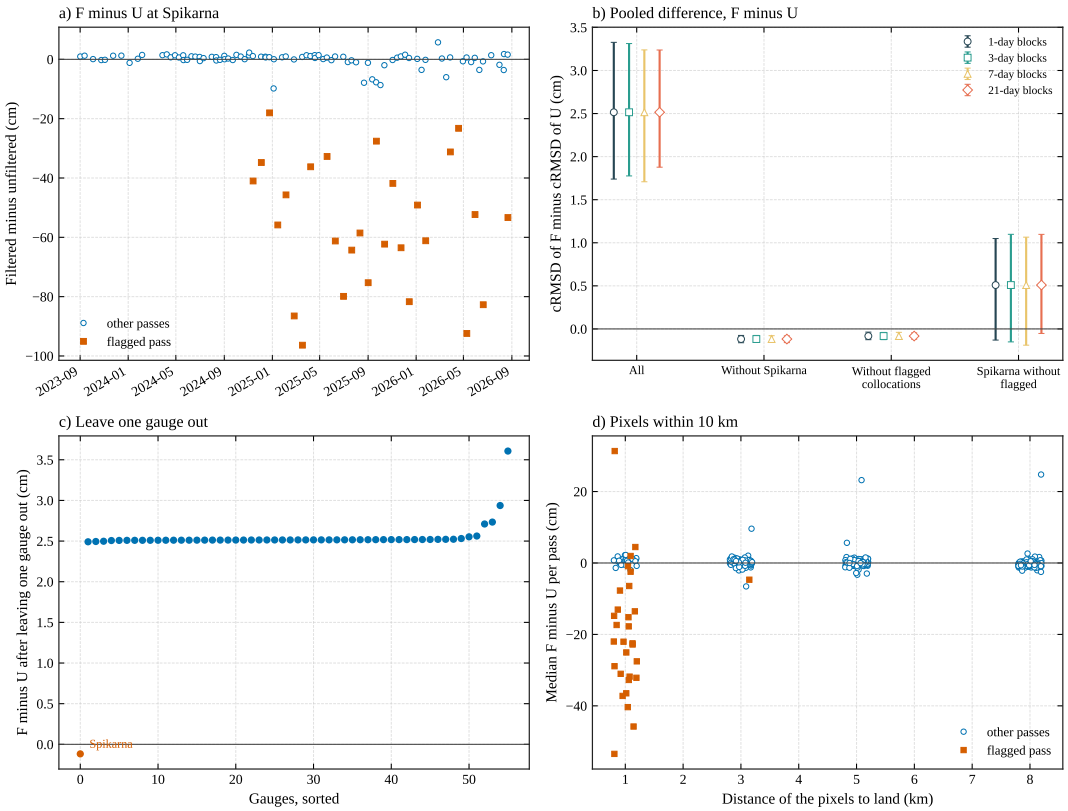


Figure S1: The filtered (F) and the unfiltered (U) anomaly against the tide gauges. (a) Filtered minus unfiltered anomaly at Spikarna, as departure from its median, for pass 29 (flagged) and the other passes. (b) Pooled cRMSD of F+DAC+OT minus that of U+DAC+OT for all collocations, without Spikarna, without the 28 flagged collocations and at Spikarna without them, with 95% confidence intervals from resampling blocks of 1 to 21 days. (c) The same difference after leaving out each gauge in turn. (d) Median filtered minus unfiltered anomaly per pass for the pixels within 10 km of Spikarna, in 2 km classes of distance to land plotted at the class centre.

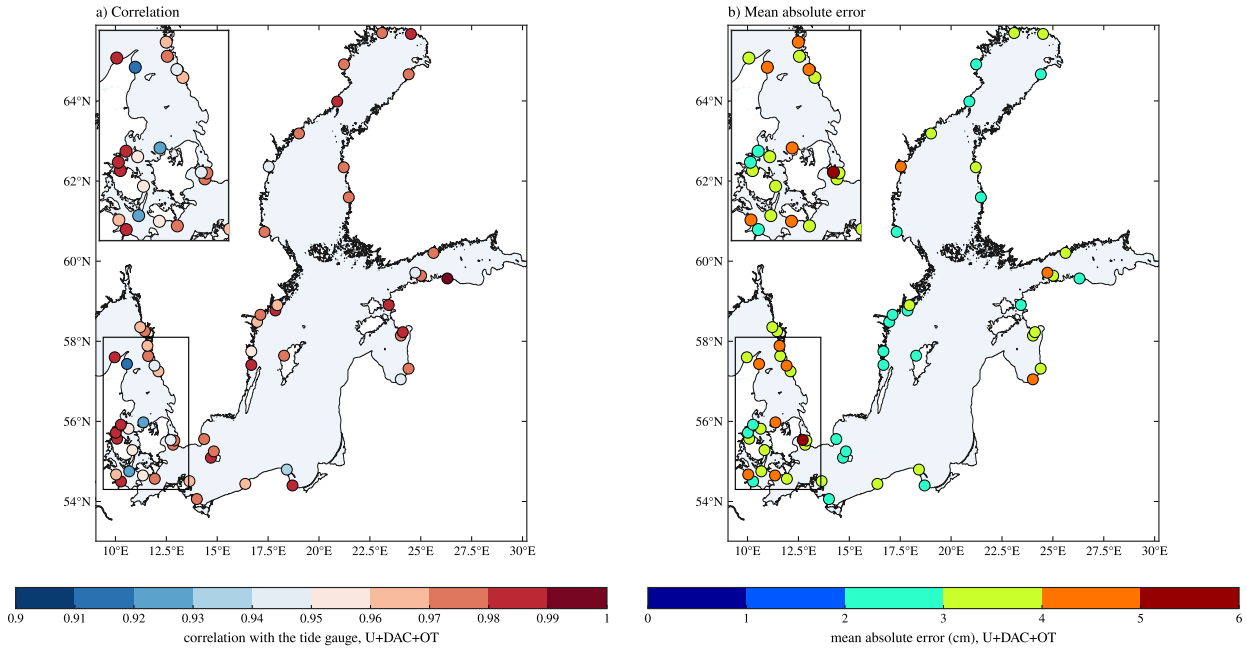


Figure S2: (a) Correlation and (b) mean absolute difference (MAE) between SWOT (U+DAC+OT) and each tide gauge used. The inset enlarges the Danish straits, marked by the rectangle.

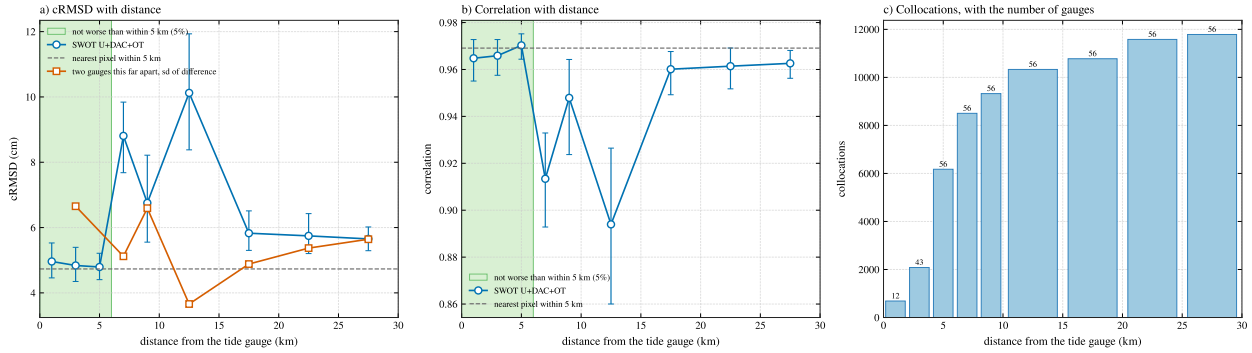


Figure S3: (a) cRMSD and (b) correlation between SWOT (U+DAC+OT) and the tide gauges for the nearest valid pixel in rings of increasing distance from the gauge, plotted at the ring centre with 95% confidence intervals. The dashed line is the nearest valid pixel within 5 km, and the shading marks the rings that are not significantly worse. Squares in (a) are the median standard deviation of the difference between the hourly anomalies of two gauges the same distance apart. (c) Collocations per ring, labelled with the number of gauges.

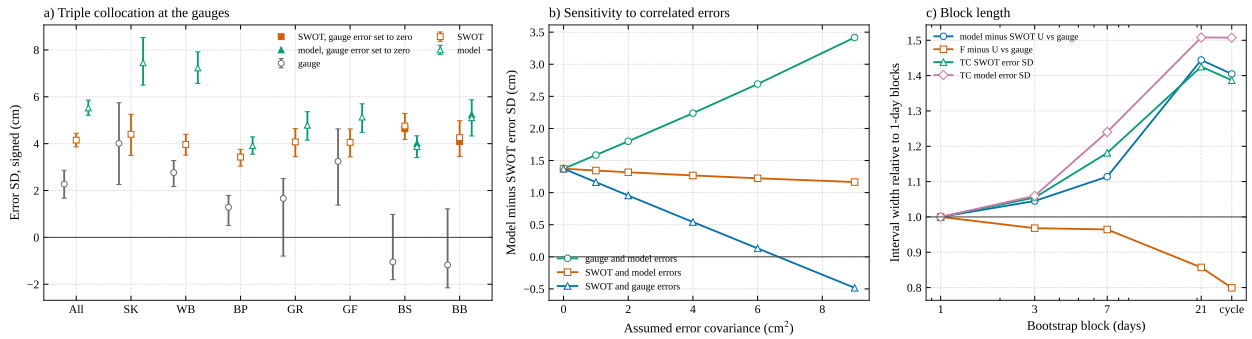


Figure S4: (a) Signed error standard deviations of the gauges, SWOT (U+DAC+OT) and the model from triple collocation at the gauge collocations, computed from the difference variances, with 95% confidence intervals, and the SWOT and model errors with the smallest gauge–model error covariance that makes the gauge error variance zero (filled). (b) Model minus SWOT error standard deviation for an assumed error covariance between each pair of data sets. (c) Width of the 95% confidence intervals relative to resampling single days, for blocks of 3 to 21 days and for whole repeat cycles.

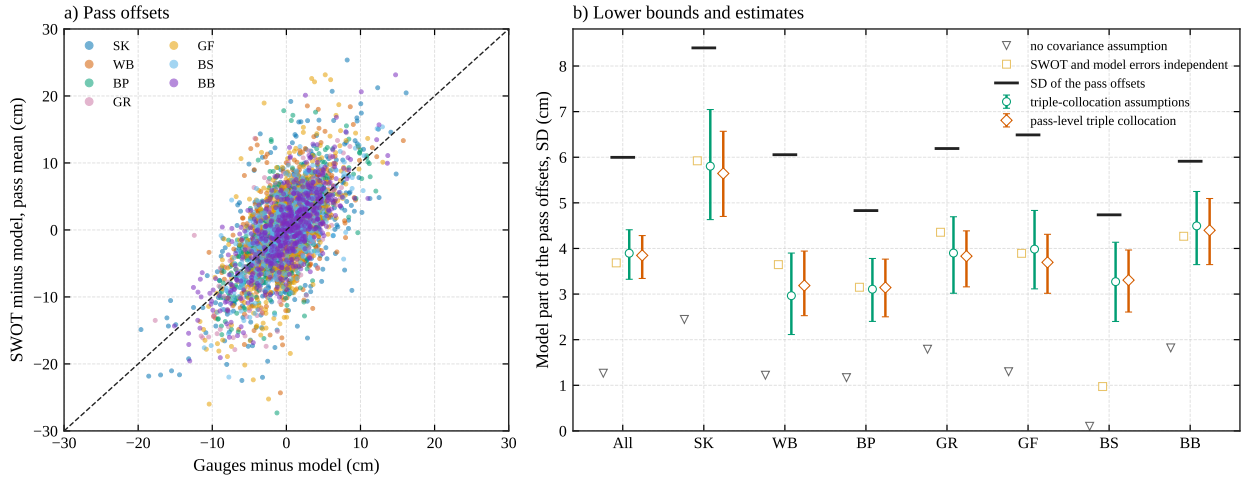


Figure S5: Attribution of the offsets uniform over a pass and sub-basin. (a) Mean SWOT minus model anomaly over each pass and sub-basin against the gauge minus model difference at the same samples. (b) Standard deviation σ_b of the model part of these offsets with no assumption on the error covariances, with SWOT and model errors independent, under the triple-collocation assumptions and from triple collocation of the offsets, with 95% confidence intervals from resampling 21-day blocks. Bars mark the standard deviation σ_u of the offsets.

Table S1: Robustness of the main results to the length of the bootstrap blocks. Value and 95% confidence interval from resampling blocks of 1, 7 and 21 days (cm unless stated), with TC for triple collocation. The rows against the tide gauges for the switches use an independent set of resamples, so their 1-day intervals differ by up to 0.06 cm from those in the main text.

Result	Value	1 day	7 days	21 days
Against the tide gauges				
DAC re-injected	−6.93	−7.54, −6.33	−7.64, −6.22	−7.73, −6.10
Ocean tide re-injected	−1.65	−1.88, −1.44	−1.89, −1.41	−1.90, −1.42
U instead of F	−2.52	−3.33, −1.74	−3.24, −1.71	−3.24, −1.88
U instead of F, without Spikarna	0.12	0.08, 0.16	0.08, 0.16	0.08, 0.16
Model minus SWOT cRMSD	1.24	0.90, 1.60	0.84, 1.63	0.74, 1.77
SWOT error, TC	4.14	3.85, 4.43	3.81, 4.50	3.74, 4.57
Model error, TC	5.50	5.17, 5.80	5.09, 5.90	4.99, 5.98
Against the model				
SWOT and model cRMSD	6.60	6.34, 6.85	6.23, 6.98	6.15, 7.03
F minus U, 0–6 km	0.67	0.53, 0.82	0.53, 0.84	0.48, 0.87
Uniform share (%)	66.26	64.18, 68.37	63.24, 69.27	62.55, 69.73
Static offset, RMSD drop	0.55	0.46, 0.62	0.45, 0.63	0.46, 0.64
Gauge offset, RMSD drop	1.38	1.19, 1.56	1.09, 1.69	1.04, 1.69
Pass offset, RMSD drop	2.26	2.12, 2.40	2.09, 2.43	2.07, 2.49
Model share of pass offsets (%)	41	38, 44	37, 45	36, 46

Table S2: Attribution of the offsets uniform over a pass and sub-basin. Number of offsets n, their standard deviation σ_u (cm) and absolute correlation $|r_{ug}|$ with the gauge-based model offset, and the standard deviation σ_b of their model part (cm) with no assumption on the error covariances (None), with SWOT and model errors independent (Indep.), under the triple-collocation assumptions (TC bound) and from triple collocation of the offsets, which also gives the SWOT part (TC model, TC SWOT) and the model share of the variance (%). The SWOT error is bounded by the SWOT minus gauge cRMSD for None and Indep. Confidence intervals for the whole area are given in Sect. S1.

Group	n	σ_u	$\lvert r_{ug}\rvert$	None	Indep.	TC bound	TC model	TC SWOT	Share
All	4293	6.00	0.65	1.26	3.68	3.90	3.85	4.60	41
Skagerrak and Kattegat	484	8.40	0.69	2.44	5.92	5.80	5.64	6.22	45
Western Baltic	540	6.06	0.49	1.22	3.65	2.96	3.19	5.15	28
Baltic Proper	977	4.83	0.64	1.17	3.15	3.11	3.14	3.67	42
Gulf of Riga	382	6.19	0.63	1.79	4.35	3.90	3.83	4.86	38
Gulf of Finland	670	6.49	0.61	1.30	3.89	3.99	3.70	5.33	32
Bothnian Sea	684	4.74	0.69	0.10	0.97	3.27	3.31	3.39	49
Bothnian Bay	556	5.91	0.76	1.82	4.27	4.49	4.40	3.95	55

Table S3: Tide gauges used, by sub-basin (SK Skagerrak and Kattegat, WB western Baltic, BP Baltic Proper, GR Gulf of Riga, GF Gulf of Finland, BS Bothnian Sea, BB Bothnian Bay) and latitude, with names as in the Copernicus Marine files. Columns give the share of hours with good hourly data (%), the collocations, the cRMSD, MAE (cm) and r of U+DAC+OT, and the change in cRMSD (cm) when the DAC or the ocean tide is removed or F replaces U. Values in parentheses are not significant at 5%.

Station		Data (%)	n	cRMSD	MAE	r	−DAC	−OT	F
Smogen	SK	99.60	167	5.40	3.72	0.97	8.63	4.83	(−0.33)
Kristineberg	SK	80.90	41	4.15	3.23	0.98	6.18	5.83	−0.34
Marstrand	SK	98.78	103	5.02	4.07	0.97	7.52	3.65	−0.47
Vinga 2	SK	91.24	170	4.80	3.59	0.97	9.30	2.84	(−0.15)
Hirtshals	SK	88.89	47	4.37	3.61	0.98	8.38	6.79	(−0.04)
Frederikshavn	SK	98.43	133	9.25	4.70	0.91	6.99	4.08	(−0.11)
Onsala	SK	99.89	86	6.16	4.70	0.94	6.43	1.05	−0.31
Ringhals	SK	98.40	48	4.19	3.40	0.97	7.85	1.96	(0.09)
Sjaellands Odde	SK	99.37	96	5.70	4.22	0.93	6.22	3.62	(−0.05)
Hov	WB	84.26	56	3.13	2.59	0.99	7.20	9.70	−0.26
Ballen	WB	99.47	29	4.38	3.69	0.96	8.84	5.39	(−0.19)
Juelsminde	WB	99.47	77	4.52	2.86	0.98	7.86	7.85	(0.06)
Bogense	WB	98.08	58	4.00	3.22	0.98	7.65	7.94	−0.26
Simrishamn	WB	99.59	58	3.27	2.44	0.98	9.03	0.55	(−0.03)
Drogden	WB	98.00	191	6.26	5.22	0.94	7.04	(0.33)	(−0.04)
Klagshamn	WB	99.94	83	4.56	3.55	0.97	7.45	(0.61)	(0.01)
Skanor	WB	99.94	131	4.53	3.43	0.97	8.72	0.58	(−0.16)
Slipshavn	WB	97.56	108	5.52	3.82	0.96	5.82	5.03	(−0.06)
Bagenkop	WB	97.56	20	5.28	3.93	0.93	6.94	(0.69)	(0.21)
Schleimuende	WB	73.13	82	5.33	4.13	0.97	11.72	1.65	(0.17)
Rodby	WB	99.14	22	5.57	4.44	0.95	9.85	1.91	−0.52
Gedser	WB	95.38	107	4.58	3.58	0.97	10.51	2.17	(0.01)
Sassnitz	WB	98.20	30	4.88	3.95	0.96	8.74	(−0.16)	(0.02)
Kiel	WB	94.99	44	3.67	2.97	0.99	13.53	1.73	(0.11)
Koserow	WB	95.57	88	3.57	2.85	0.98	8.97	(0.47)	(0.04)
Rohukula	BP	95.36	33	3.51	2.66	0.98	6.29	0.98	(−0.18)
Nynas Fiskehamn	BP	94.48	51	4.62	3.71	0.97	2.17	0.63	(−0.24)
Landsort Norra	BP	99.93	167	3.21	2.51	0.98	4.09	0.41	−0.22
Oxelosund Vinterklasen	BP	99.71	76	3.95	2.73	0.97	4.21	(0.19)	−0.40
Arko	BP	99.79	114	3.84	2.98	0.96	3.23	(0.20)	−0.54
Vastervik	BP	98.97	20	3.63	2.66	0.96	(1.61)	(0.76)	−0.72
Visby	BP	99.83	35	3.55	2.79	0.98	3.97	(−0.05)	−0.40
Simpevarp	BP	96.59	93	2.96	2.22	0.98	4.71	0.41	(−0.06)
Tejn	BP	98.58	23	2.82	2.34	0.97	4.42	0.82	(−0.04)
Ronne	BP	65.83	53	3.06	2.58	0.99	7.11	0.80	(−0.06)
Wladyslawowo	BP	92.20	41	4.94	3.88	0.94	4.07	(0.14)	(−0.11)
Darlowo	BP	92.61	36	4.51	3.56	0.96	5.33	(−0.38)	−0.52
Gdansk	BP	92.14	24	3.29	2.63	0.98	8.47	(0.02)	(−0.03)
Munalaiu	GR	97.19	128	4.05	3.23	0.98	7.76	1.67	(0.16)
Kihnu	GR	97.29	67	4.41	3.54	0.97	6.32	1.03	(−0.01)
Skulte	GR	93.64	35	4.73	3.60	0.98	5.37	1.44	(0.16)
Daugavgriva	GR	96.52	21	5.65	4.24	0.94	6.02	(0.80)	(0.02)
Porvoo	GF	99.29	138	4.56	3.46	0.97	5.16	1.45	(−0.03)
Tallinnamadal	GF	54.38	101	6.74	4.49	0.95	4.13	0.66	(0.05)
Kelnase	GF	55.66	67	4.55	3.50	0.97	8.21	(0.11)	−0.24
Eisma	GF	85.22	32	2.89	2.31	0.99	8.69	1.91	−0.41
Skagsudde 2	BS	92.05	141	3.94	3.14	0.97	5.55	(0.09)	−0.54
Spikarna	BS	99.93	116	5.80	4.11	0.95	3.49	(0.06)	22.08
Kaskinen	BS	99.09	67	4.51	3.25	0.97	3.59	(0.20)	(−0.13)
Pori	BS	99.24	34	3.82	3.00	0.97	3.41	0.44	(−0.19)
Bonan	BS	99.03	38	3.86	2.81	0.98	5.17	(0.09)	(0.03)
Kalix Storon	BB	99.94	91	4.47	3.20	0.98	10.04	(0.23)	(−0.03)
Kemi	BB	99.41	63	4.33	3.18	0.98	12.27	0.53	(−0.27)
Furuogrund	BB	97.97	21	3.25	2.79	0.98	4.22	(0.32)	(−0.23)
Raahe	BB	99.35	39	3.59	2.74	0.98	8.81	1.02	(0.04)
Ratan	BB	99.92	47	3.69	2.91	0.98	9.21	0.38	(−0.17)

Table S4: SWOT (U+DAC+OT) against the tide gauges for the nearest valid pixel in each distance ring, with the number of gauges and collocations, cRMSD (cm) and correlation, paired change in cRMSD against the nearest valid pixel within 5 km (cm), and the number of gauge pairs at the same distance with the median standard deviation of their hourly difference (cm). Intervals are 95% confidence intervals.

Ring (km)	Gauges	n	cRMSD	r	Paired ΔcRMSD	Pairs, standard deviation
0–2	12	687	4.96 (4.46, 5.53)	0.96	0.00 (same pixels)	–
2–4	43	2083	4.84 (4.35, 5.39)	0.97	−0.04 (−0.08, 0.00)	1, 6.65
4–6	56	6174	4.79 (4.40, 5.21)	0.97	−0.10 (−0.17, −0.04)	–
6–8	56	8503	8.81 (7.68, 9.84)	0.91	6.28 (4.71, 7.74)	3, 5.12
8–10	56	9325	6.76 (5.55, 8.22)	0.95	1.98 (1.15, 2.93)	3, 6.59
10–15	56	10331	10.12 (8.38, 11.93)	0.89	7.99 (5.35, 10.50)	17, 3.66
15–20	56	10777	5.83 (5.30, 6.51)	0.96	1.15 (0.64, 1.75)	31, 4.88
20–25	56	11581	5.75 (5.20, 6.43)	0.96	0.34 (0.15, 0.55)	18, 5.37
25–30	56	11787	5.65 (5.29, 6.02)	0.96	0.62 (0.32, 0.98)	35, 5.64

Table S5: Model against the tide gauges, hourly, by time scale. Error standard deviation (cm) of variations slower than 30 days, between 2 and 30 days and faster than 2 days, share of each removed by the sub-basin offset estimated from the other gauges (%), and RMSD (cm) of the anomalies before and after removing that offset, for all gauges with good data in at least half of the hours.

	Error standard deviation			Removed (%)			RMSD	
Group	Slow	2–30 d	Fast	Slow	2–30 d	Fast	Before	After
All	2.87	3.01	4.55	72	67	12	6.35	4.87
Skagerrak and Kattegat	2.73	4.63	7.04	75	80	17	9.15	6.85
Western Baltic	3.04	3.38	6.03	47	35	11	7.69	6.71
Baltic Proper	2.62	2.04	2.78	71	56	1	4.56	3.46
Gulf of Riga	3.01	2.51	3.69	63	77	11	5.54	4.11
Gulf of Finland	3.03	2.73	5.09	69	54	4	6.56	5.51
Bothnian Sea	2.52	1.92	2.14	91	72	4	4.07	2.50
Bothnian Bay	3.05	3.02	2.73	93	83	20	5.35	2.87