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Update on CryoSat-2 long-term ocean data analysis and validation

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1. Abstract

As CryoSat-2 ocean products continuously evolve, they need to be quality controlled and thoroughly validated via science-oriented diagnostics based on multi-platform in situ data, models and other (altimeter) satellite missions. The rationale for this is the scientific roadmap addressing key challenges in long-term monitoring of sea-level and ocean circulation changes due to Global Warming.

We persistently monitor, analyze and identify systematic errors in the data, and estimate (trends in) biases in range, significant wave height, backscatter, wind speed and sea state. We found that GOP CryoSat-2 Baseline-C data has a range bias of -2.92 cm and no apparent drift w.r.t. altimeter reference missions (<+0.1 mm/yr). This bias appears to depend on mode (SAR/LRM) and whether a pass is ascending or descending. The comparison with monthly averaged sea level from a selection of 185 PSMSL tide gauges shows a correlation >0.84, average SD < 5.8 cm, and a -0.19 mm/yr drift, translating to an overall trend of +0.11 mm/yr when applying a global GIA correction of +0.3 mm/yr. So, CryoSat-2 GOP is (long-term) stable.

2. CryoSat-2 and concurrent altimetry

We convert CryoSat-2 GOP Baseline-C data to RADS from 2010 to 2022. Changes only concern timings (different offset) and reference (WGS84 to TOPEX ellipsoid). Table 1 presents the dual crossover (XO) statistics with all concurrent altimeter missions, revealing the different absolute biases. We conclude from the average that GOP has a bias of -2.92 cm and from the rms (2.75 cm) that GOP is on par with the Jasons, the Sentinels and SARAL. Then we analyse the bias between LRM and SAR mode: w.r.t. J2 we find a mutual bias of ≈1.5 cm. Partly explained by an LRM/SAR bias in SSB (0.6 cm). As most other corrections are (close) to identical we think that it also can be explained by different re-trackers, though we also discovered a difference between ascending and descending passes of 0.9 cm. This is under investigation. Figures 1 and 2 summarize these bias findings.

w.r.t.	SLA [m]		SWH [m]		σ^0 [dB]		WIND [m/s]		SSB [m]	
	mean	rms	mean	rms	mean	rms	mean	rms	mean	rms
J2	-0.0282	0.0271	0.0053	1.1953	-0.2605	1.6302	0.1683	3.9465	-0.0375	0.0448
J3	-0.0249	0.0272	0.0099	1.2042	-0.4851	1.6544	0.3684	3.9813	-0.0383	0.0451
3A	-0.0292	0.0270	-0.0945	1.1362	-0.1305	1.6964	-0.1689	3.6955	-0.0063	0.0429
3B	-0.0268	0.0264	-0.1070	1.1318	-0.1914	1.7013	0.0172	3.6508	-0.0062	0.0429
SA	-0.0320	0.0280	-0.0435	1.1275	0.0677	1.7432	-0.1039	3.5729	-0.0066	0.0425
SB	-0.0318	0.0276	-0.0293	1.1201	0.0107	1.7612	0.0103	3.5838	-0.0070	0.0424
$C2^{rads}$	-0.0314	0.0289	-0.1369	1.0423	-0.0236	1.7985	-0.4344	3.5429	0.0182	0.0467
avg.	-0.0292	0.0275	-0.0566	1.1368	-0.1447	1.7122	-0.0204	3.7105	-0.0120	0.0439

Table 1: (top) Dual-satellite GOP XO statistics. Only XOs considered with Δt < 5 days, –70°< lat <+70°, and < 1x st. dev.

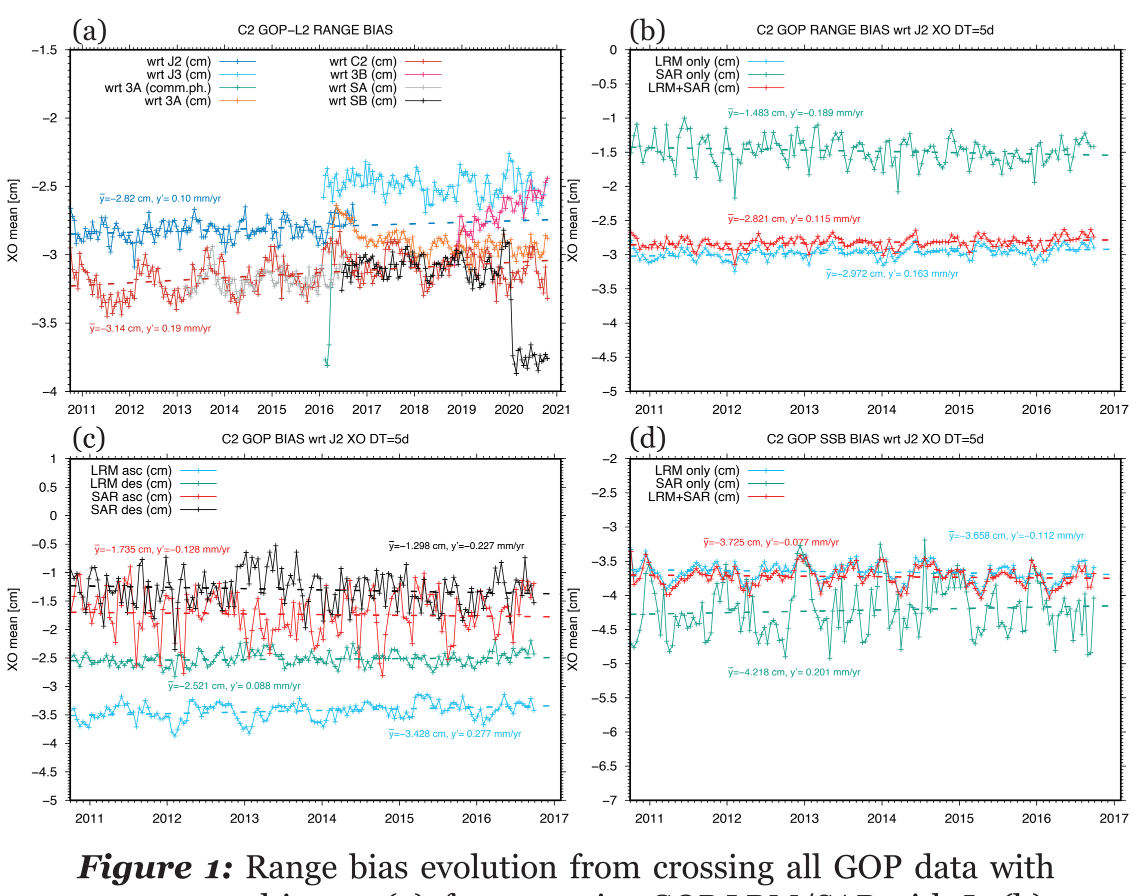

Figure 1: Range bias evolution from crossing all GOP data with concurrent altimetry (a), from crossing GOP LRM/SAR with J2 (b), from crossing GOP asc/dec LRM/SAR with J2 (c), and sea state bias evolution from crossing GOP LRM/SAR with J2 (d).

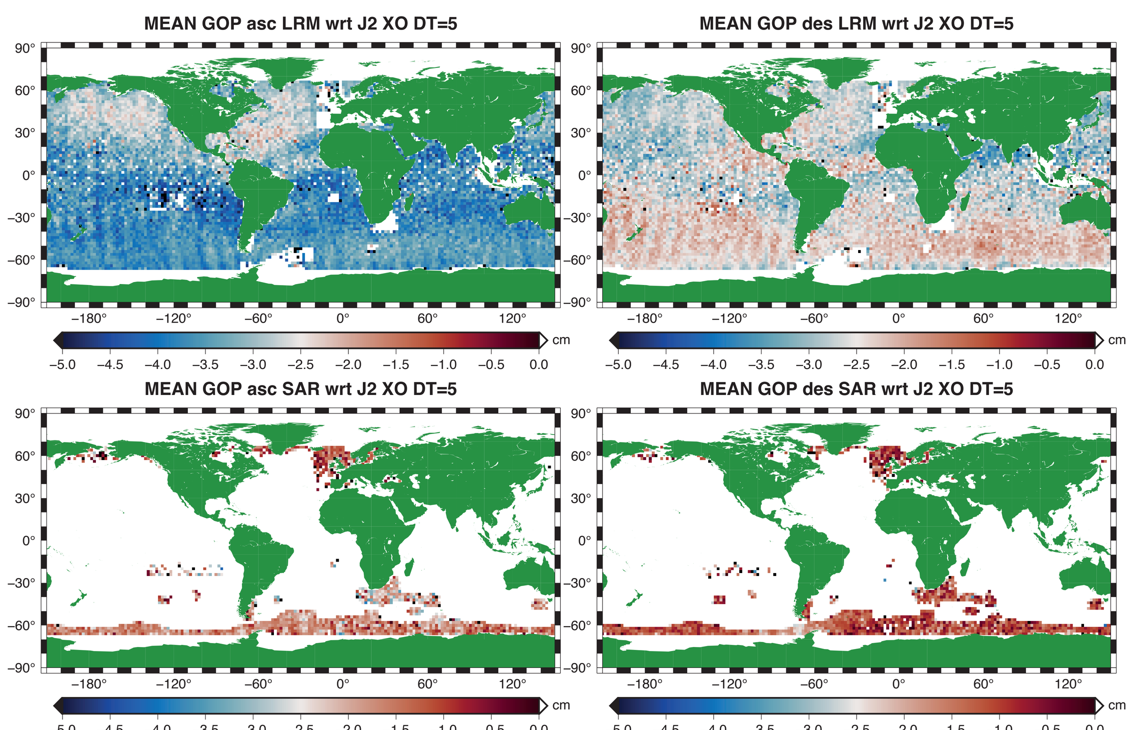

Figure 2: Regional distribution of GOP/J2 XO mean values separated in LRM (top) and SAR (bottom) and separated in ascending (left) and descending (right). The asc/des difference is a concern.

2. Numerical ocean models

In this section we look into the accuracy and the validity of the sea state bias (SSB) models for CryoSat-2. We make a distinction between parametric (BM4-model) and non-parametric models both incorporating significant wave height and wind speed. Comparisons are made to Jason-3 and Sentinel-6A, either taking altimetric Ku-band wind or ECMWF derived winds. For the parametric solution the parameters are directly estimated (fitted) from XOs: At a crossing location we find for the observed sea level height a difference that is determined with the help of a least-squares estimator. Table 2 lists the parameter values for 6 cases. The performance of the parametric models is expressed in two ways, namely via the pre-fit and post-fit standard deviations of residuals at XOs and the explained variance by the approach. This is addressed in Table 3: "Pre-fit" is st. dev. at XOs when not applying SSB, "Post-fit P" is std.dev. when the parametric BM4 model coefficients are solved, obviously reducing the st. dev. of the remaining signal. The % by which it is reduced is in column "Var P". Columns "Post-fit NP" and "Var NP" show the results after the non-parametric fit, and columns "Post-fit OP" and "Var OP" show the data original SSB. The non-parametric approach to estimate the SSB model is different from Gaspar et al, 1998: we first estimate a parametric model, and then perform a Kriging procedure (see: Press et al, 2007) to map the residuals between the observed data and the parametric model in a matrix of residuals:

$$\mathrm{SSB_{NP}} = \mathrm{SSB_P} + \frac{\sum_{ij}^{\max(\rho)} \mathrm{dSSB}_{ij} e^{-\rho(\mathrm{SWH},U)^2/\tau^2}}{\sum_{ij}^{\max(\rho)} e^{-\rho(\mathrm{SWH},U)^2/\tau^2}}$$

In Figures 3a and 3b we show the resulting non-parametric model SSB grids taking the altimetric winds and ECMWF winds, resp. In Figures 3c and 3d the background SSB parametric models are displayed again with altimetric wind and ECMWF winds, resp.

Case	Wind	a_1	a_2	a_3	a_4	ndata
J3	Ku	-0.039964172	0.002476889	-0.002088632	0.000080290	3752963
S6A	Ku	-0.039247863	0.001988374	-0.001559993	0.000062647	629924
C2	Ku	-0.035017731	0.002377262	-0.003127031	0.000112225	918664
J3	ECMWF	-0.045452330	0.002510686	-0.001533930	0.000066477	3752963
S6A	ECMWF	-0.042963576	0.002001314	-0.001132749	0.000050535	629924
C2	ECMWF	-0.045250227	0.002605681	-0.002137882	0.000080645	918664

Table 2: BM4 model parameters for 6 cases, units in m and m/s.

Sat	Wind	Pre-fit	Post-fit P	Post-fit NP	Post-fit OP	Var P	Var NP	Var OP
J3	Ku	8.858	6.996	6.959	6.954	37.61	38.27	38.37
S6A	Ku	8.833	7.463	7.396	7.396	28.61	29.88	29.88
C2	Ku	8.553	7.052	7.018	7.445	32.02	32.67	24.24
J3	ECMWF	8.858	7.016	6.973	6.954	37.27	38.02	38.37
S6A	ECMWF	8.833	7.473	7.408	7.396	28.42	29.65	29.88
C2	ECMWF	8.553	7.089	6.973	7.445	31.31	33.53	24.24

Table 3: Statistics of several (non-)parametric SSB models.

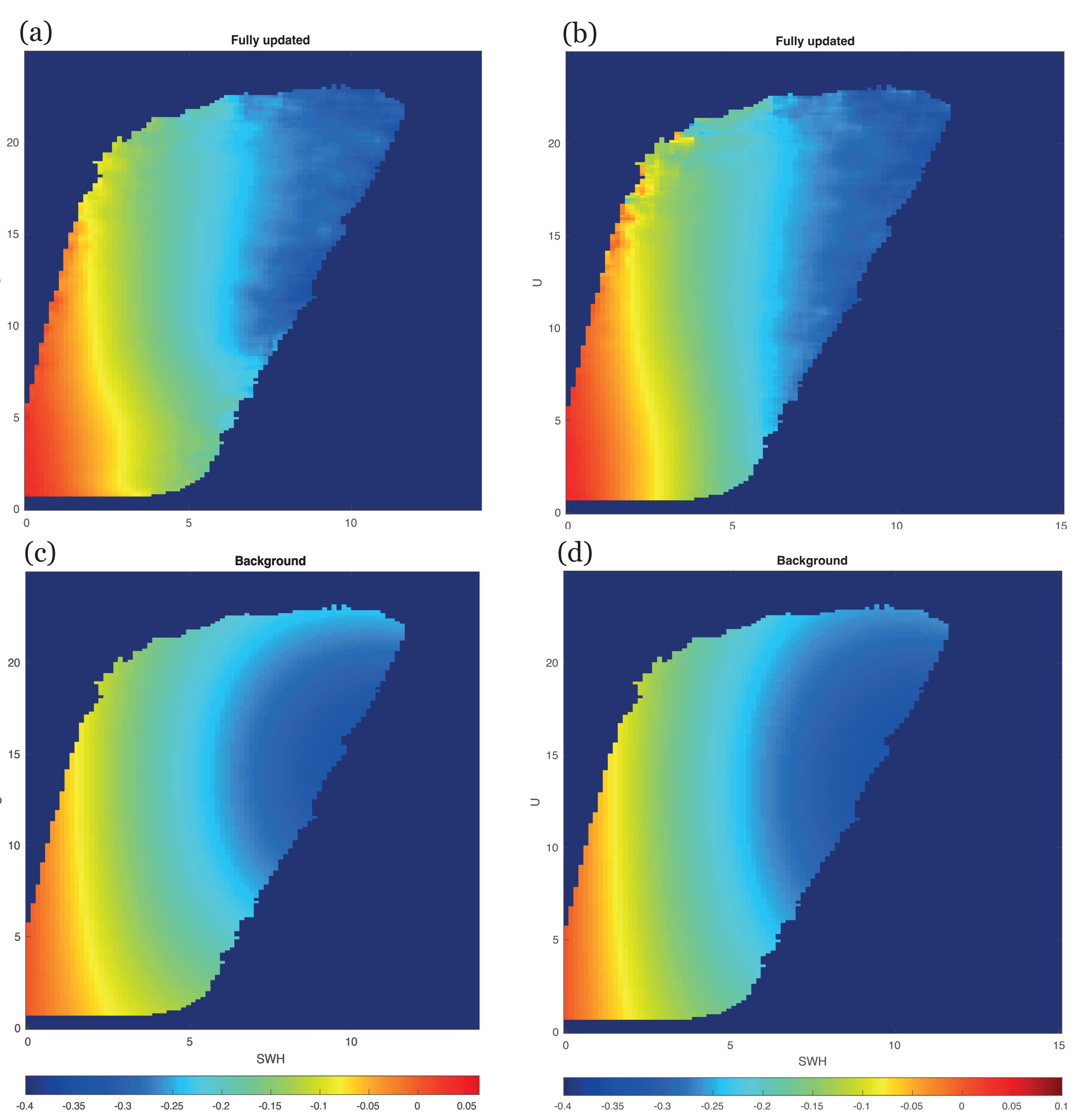

Figure 3: (Top) CryoSat-2 SSB_NP grids based on original winds (left) and ECMWF winds (right), and (bottom) CryoSat-2 SSB_P parametric solutions (BM4 model) again with original wind (left) and ECMWF winds (right).

We conclude that more sea level XO variance can be explained by a tuned non-parametric SSB model. We notice that GOP SSB can be improved considerably unlike any of the other satellites, so we propose for CryoSat-2 to use this tailored non-parametric model based on altimetric SWH and ECMWF wind. It is unlikely that choosing a different SSB model wil lead to changes in the long-term stability as long both SWH and wind speed don't exhibit long-term trends (which we do not observe).

3. Concurrent in situ data

Here we make a direct comparison of the GOP Baseline-C sea level data with those of a selected set of PSMSL tide gauges (TG). To ensure identical physical content of altimetry and TG, we (a) use monthly averaged TG data to filter out the high frequency tidal and atmospheric signal, (b) use the TG Revised Local Reference data, (c) take TG/Altim data from 2010 to 2020, (d) apply all standard corrections to the altimeter, including geocentric ocean tide correction (GOT410), mean sea surface CNESCLS15, and HF part of the atmospheric signal (leaving out LF static IB), (e) grid monthly altimeter solutions with σ=0.5°, horizon=3σ, and gridspacing=0.25°, (f) use `grdtrack` (GMT) to produce altimetric sea level time series at the TG locations, and (g) remove a common bias.

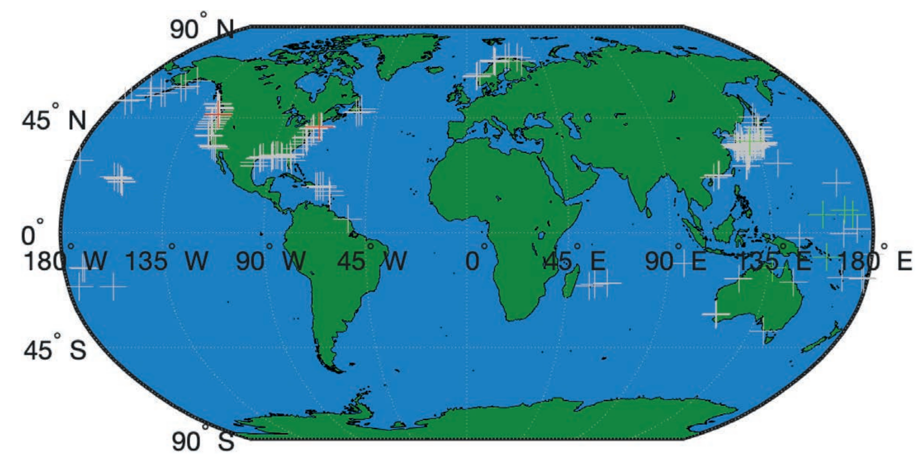

Figure 4: Map of selected TG stations. These are edited by requiring no data gaps in 2010–2021, correlation with GOP sea level data R>0.7, RMS difference σ < 0.15m, and trend difference < 10mm/yr, which reduced the number of stations to 185 (white plusses). Light green plusses represent the 6 best fits and red plusses the 2 worst.

For the stations in Figure 4, we compare SLA with TG and compute R and SD. Table 4 summarizes the average statistics for both the CryoSat-2 GOP (CG) and RADS (C2) data. If we introduce the mean rate of sea level change due to global isostatic adjustment estimated at ≈ −0.3 mm/yr ±50%, the bias drift becomes -0.19 + 0.3 = 0.11 mm/yr and is compatible with the found range stability from XO analyses with the reference mission J2. Note that in the difference, any "natural" sea level rise would cancel. Figure 5 shows four of the best fits. Checking in detail the differences we conclude that the GOP product is stable and to a certain extent outperforms RADS.

	Correlation [-]	st. dev. [cm]	tilt [mm/yr]
CG −TG	0.84	5.8	−0.19
C2 − TG	0.83	6.0	−0.45

Table 4: Summary of GOP (CO) and RADS CryoSat-2 (C2) comparison with PSMSL tide gauges (TG), for 185 selected tide gauge stations, for the period 2010 until 2020.

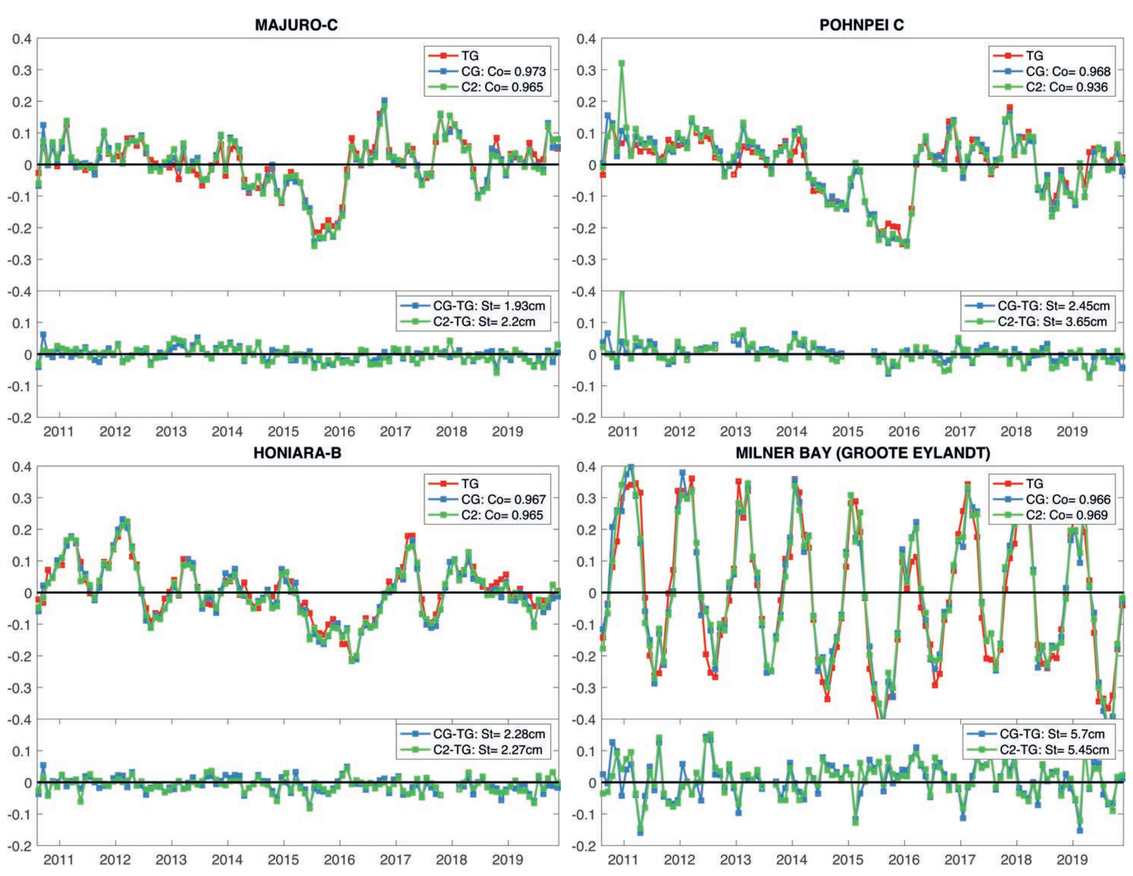

Figure 5: Sea level comparisons: PSMSL tide gauges with GOP and RADS CryoSat-2 for the four best results, based on correlation.

4. Conclusions

GOP Baseline-C ocean data has a −2.9 cm range bias w.r.t. the calibrated reference satellites in RADS and neglible drift. When separated in SAR and LRM mode we find a mutual bias of ≈1.5 cm, which is explained by an LRM/SAR SSB bias of 0.6 cm and a 0.9 cm bias between ascending and descending passes. The Baseline-C SSB model can be significantly improved by a non-parametric approach using altimetric SWH and ECMWF wind. A selection of 185 PSMSL tide gauges and GOP have an average correlation R = 0.84, average SD σ = 5.8 cm, and a drift of −0.19 mm/yr. Overall GOP performance is clearly on par with the altimeter reference missions.

5. Acknowledgments

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