

Attributing uncertainties in elevation assessments for data-sparse coastal lowlands using global elevation models: A globally applicable approach showcasing the Vietnamese Mekong Delta

Katharina Seeger^{1,2,3*}, and Philip S.J. Minderhoud^{1,3,4}

¹Soil Geography and Landscape Group, Wageningen University & Research; Wageningen, NL-6708PB, Netherlands

²Institute of Geography, University of Cologne; Cologne, 50923, Germany

³Department of Civil, Environmental and Architectural Engineering, University of Padova; Padova, Italy

⁴Department of Subsurface and Groundwater Systems, Deltares Research Institute; Utrecht, The Netherlands

*katharina.seeger@wur.nl, katharina.seeger@unipd.it, k.seeger@uni.koeln.de

Supplementary Information

Performance of digital elevation models in the Vietnamese Mekong Delta

Which one is the best? – On the local validation of global satellite-based digital elevation models: Comparison with local point elevations

Extracting local point elevations from the respective global DEMs in form of a spot height comparison reveals similar results as the spatial comparison with TopoDEM_v2 and yields only slight changes in the error and height residual statistics. For most of the DEMs which are comparably higher than indicated by local elevation, error metrics lower by ca. 2–5 cm compared to the statistics of the comparison to TopoDEM_v2 (Table 2; Supplementary Table 1). For those DEMs that perform already well in comparison with TopoDEM_v2 (i.e. DeltaDTM) or are on average consistent with the local data (i.e. CoastalDEM v2.1), pointwise determined average errors slightly increase and height residuals become (more) negative while for GLL-DTM v2, at least mean error reduces further. This pattern holds true for the comparison with low-lying spot heights (i.e. ≤ 10 m) as well (Table 2; Supplementary Table 2). Probably the most remarkable difference between DEM spatial comparison and validation by local point elevations is the decrease of median height residual for SRTM by 13–14 cm to 0.04 m for point elevation comparison with all and only low-elevation spot heights, respectively (Supplementary Tables 1 and 2). However, we do not consider these slight changes as significant but rather explain them by respective capacities and limitations to resolve local point settings. Instead, we interpret the results of this point elevation comparison being similar to outcomes of the spatial comparison with TopoDEM_v2 and to strengthen our overall finding that among the assessed DEMs, most recently processed coastal elevation data provides the most accurate results, of which we strongly recommend the usage of DeltaDTM v1 referenced to local continuous, actual MSL, which shows the overall best agreement with local elevation data in the Vietnamese Mekong Delta.

DEM	N	Mean spot (m)	Median spot (m)	Min. spot (m)	Max. spot (m)	Mean DEM (m)	Median DEM (m)	Min. DEM (m)	Max. DEM (m)	σ DEM (m)	Max. negative HR (m)	Max. positive HR (m)	Mean error (m)	MAE (m)	Median error (m)	RMSE (m)
TopoDEM_v2	18447	0.79	0.66	-1.06	9.95	0.77	0.70	-0.34	7.58	0.60	2.46	-4.76	-0.03	0.13	0.01	0.26
Topo DEM v1	18685	0.80	0.67	-1.06	9.95	0.82	0.74	-0.49	6.91	0.60	-9.25	1.10	-0.03	0.13	0.01	0.26
SRTM _{MDT}	18865	0.83	0.67	-1.06	99.95	0.98	0.83	-6.75	72.99	2.55	-52.76	54.18	0.15	1.85	0.04	2.52
SRTM _{EGM06}	18997	0.83	0.67	-1.06	99.95	2.21	2.04	-6.72	74.46	2.60	-51.63	55.24	1.38	2.17	1.28	2.89
ACE2 _{MDT}	16809	0.80	0.66	-1.06	99.95	0.97	0.86	-5.98	80.84	1.87	-26.38	24.26	0.17	1.24	0.11	1.65
ACE2 _{EGM06}	16853	0.80	0.66	-1.06	99.95	2.23	2.12	-5.11	82.31	1.94	-25.23	25.19	1.44	1.75	1.38	2.21
MERITDEM _{MDT}	18365	0.80	0.66	-1.06	99.95	2.02	1.94	-3.32	79.04	1.26	-24.13	26.85	1.22	1.35	1.24	1.60
MERITDEM _{EGM06}	18367	0.80	0.66	-1.06	99.95	3.29	3.25	-5.15	80.51	1.35	28.09	-22.98	2.49	2.52	2.52	2.72
ASTGTM v003 _{MDT}	19028	0.83	0.67	-0.45	99.95	8.60	7.46	-1.23	80.07	5.08	-53.20	80.22	7.78	7.80	6.63	9.36
ASTGTM v003 _{EGM06}	19028	0.83	0.67	-0.45	99.95	9.87	8.76	0.00	80.89	5.08	-52.07	81.04	9.04	9.05	7.91	10.42
AW3D30 _{MDT}	15977	0.84	0.68	-1.06	61.95	1.27	1.02	-6.27	43.07	2.43	-51.17	41.13	0.43	1.73	0.25	2.48
AW3D30 _{EGM06}	16055	0.84	0.68	-1.06	61.95	2.50	2.22	-6.97	44.14	2.50	-50.04	42.19	1.66	2.19	1.50	2.99
TanDEM-X _{MDT}	18162	0.81	0.66	-1.06	99.95	1.69	1.17	-5.40	81.73	1.82	26.80	-59.40	0.89	1.06	0.41	1.92
TanDEM-X _{EGM06}	18167	0.81	0.66	-1.06	99.95	2.94	2.47	-3.79	83.20	1.84	-58.28	28.05	2.14	2.17	1.68	2.72
Copernicus DEM _{MDT}	16479	0.88	0.75	-0.45	99.95	1.68	1.07	-4.15	62.50	1.98	-48.42	60.56	0.80	1.09	0.22	2.07

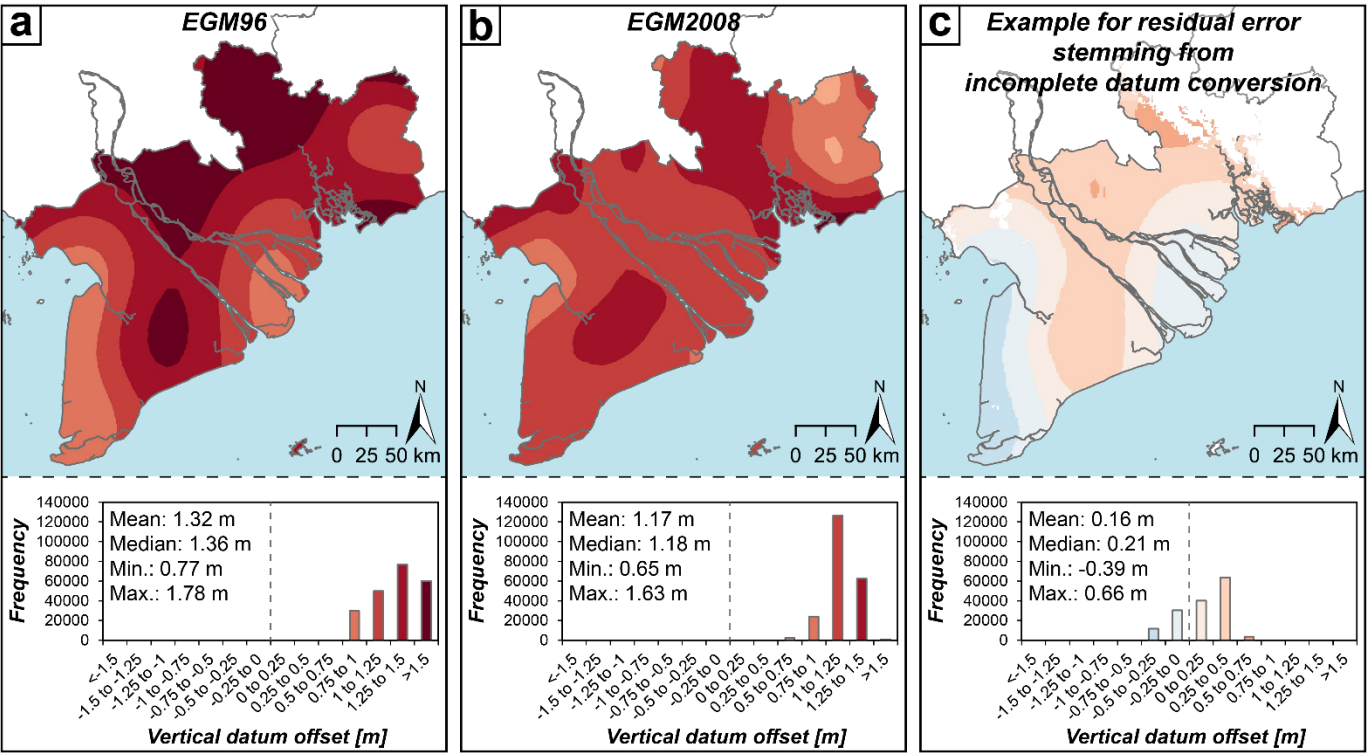
Copernicus DEM _{EGM2008}	16479	0.88	0.75	-0.45	99.95	2.87	2.26	-2.92	63.55	1.98	-47.32	61.61	1.98	2.01	1.40	2.74
FABDEM _{MDT}	14605	0.87	0.75	-0.45	99.95	1.28	1.03	-1.51	80.92	1.30	-19.02	28.25	0.41	0.62	0.23	1.10
FABDEM _{EGM2008}	16341	0.88	0.75	-0.45	99.95	2.45	2.18	-0.92	67.74	1.37	-52.92	43.62	1.57	1.60	1.37	2.00
CoastalDEM v2.1 _{MDT}	18961	0.83	0.67	-1.06	99.95	0.75	0.78	-2.46	69.86	1.26	-60.23	36.45	-0.08	0.82	-0.02	1.25
CoastalDEM v2.1 _{EGM96}	18940	0.83	0.67	-1.06	99.95	2.02	2.00	-1.15	53.92	1.29	-58.87	51.47	1.20	1.37	1.20	1.78
GLL-DTM v2 _{MDT(this study)}	17346	0.76	0.66	-0.45	9.95	0.81	0.75	-0.51	7.02	0.55	-8.47	4.12	0.05	0.33	0.09	0.46
GLL-DTM v2 _{MDT(original)}	17354	0.76	0.66	-0.45	7.98	0.95	0.89	-0.75	7.19	0.68	-7.51	4.19	0.19	0.42	0.26	0.55
DeltaDTM v1 _{MDT}	14055	0.86	0.75	-0.45	7.98	0.75	0.68	-1.88	6.77	0.61	-7.35	4.71	-0.11	0.36	-0.11	0.52
DeltaDTM v1 _{EGM2008}	16479	0.86	0.75	-0.45	9.95	1.94	1.84	-0.98	9.77	0.70	-7.09	7.20	1.07	1.11	1.11	1.21
DeltaDTM v1.1 _{MDT}	16462	0.87	0.75	-0.45	25.95	0.63	0.53	-3.55	28.95	0.77	-25.09	27.01	-0.24	0.40	-0.19	0.67
DeltaDTM v1.1 _{EGM2008}	16462	0.87	0.75	-0.45	25.95	1.81	1.70	-2.32	30.00	0.79	-23.98	28.06	0.94	0.99	1.00	1.13

Supplementary Table 1. Performance of local and global DEMs in the Vietnamese Mekong Delta validated by local point elevations for versions referenced to mean dynamic topography (MDT) and their original vertical reference. N – number of spot heights in the study area, with no-data values excluded for each DEM, respectively; Mean spot – mean point elevation in the study area; Median spot – median point elevation in the study area; Min. spot – minimum point elevation in the study area; Max. spot – maximum point elevation in the study area; Mean DEM – mean DEM elevation in the study area; Median DEM – median DEM elevation in the study area; Min. DEM – minimum DEM elevation in the study area; Max. DEM – maximum DEM elevation in the study area; σ DEM – standard deviation of DEM elevation in the study area; HR – height residual; MAE – mean absolute error; RMSE – root mean square error.

DEM	N	Mean spot (m)	Median spot (m)	Min. spot (m)	Max. spot (m)	Mean DEM (m)	Median DEM (m)	Min. DEM (m)	Max. DEM (m)	σ DEM (m)	Max. negative HR (m)	Max. positive HR (m)	Mean error (m)	MAE (m)	Median error (m)	RMSE (m)
TopoDEM_v2	18447	0.79	0.66	-1.06	9.95	0.77	0.70	-0.34	7.58	0.60	-4.76	2.46	-0.03	0.13	0.01	0.26
Topo DEM v1	18685	0.80	0.67	-1.06	9.95	0.82	0.74	-0.49	6.91	0.60	-9.25	1.10	-0.03	0.13	0.01	0.26
SRTM _{MDT}	18858	0.82	0.67	-1.06	9.95	0.98	0.82	-6.75	56.12	2.49	-9.83	54.18	0.16	1.84	0.04	2.48
SRTM _{EGM96}	18990	0.82	0.67	-1.06	9.95	2.20	2.04	-6.72	57.19	2.55	-8.33	55.24	1.39	2.16	1.28	2.83
ACE2 _{MDT}	16806	0.79	0.66	-1.06	9.95	0.96	0.86	-5.98	25.10	1.76	-6.98	24.26	0.17	1.24	0.11	1.63
ACE2 _{EGM96}	16850	0.79	0.66	-1.06	9.95	2.23	2.12	-5.11	26.04	1.83	-5.42	25.19	1.44	1.75	1.38	2.20
MERITDEM _{MDT}	18362	0.79	0.66	-1.06	9.95	2.02	1.94	-3.32	30.80	1.10	-5.37	26.85	1.22	1.34	1.25	1.58
MERITDEM _{EGM96}	18364	0.79	0.66	-1.06	9.95	3.28	3.25	-5.15	32.04	1.20	-6.12	28.09	2.49	2.52	2.52	2.70
ASTGTM v003 _{MDT}	19023	0.82	0.67	-0.45	9.95	8.60	7.46	-1.23	80.07	5.06	-4.44	80.22	7.79	7.79	6.63	9.35
ASTGTM v003 _{EGM96}	19023	0.82	0.67	-0.45	9.95	9.86	8.76	0.00	80.89	5.06	-3.25	81.04	9.05	9.05	7.91	10.41
AW3D30 _{MDT}	15971	0.83	0.68	-1.06	9.95	1.26	1.02	-6.27	43.07	2.42	-7.74	41.13	0.44	1.72	0.25	2.41
AW3D30 _{EGM96}	16049	0.83	0.68	-1.06	9.95	2.50	2.22	-6.97	44.14	2.49	-7.65	42.19	1.67	2.19	1.50	2.95
TanDEM-X _{MDT}	18155	0.79	0.66	-1.06	9.95	1.69	1.17	-5.40	29.25	1.72	-6.35	26.80	0.90	1.05	0.41	1.81
TanDEM-X _{EGM96}	18160	0.79	0.66	-1.06	9.95	2.94	2.47	-3.79	30.49	1.73	-4.74	28.05	2.15	2.16	1.68	2.65
Copernicus DEM _{MDT}	16474	0.87	0.75	-0.45	9.95	1.67	1.07	-4.15	62.50	1.93	-5.17	60.56	0.81	1.08	0.22	2.00
Copernicus DEM _{EGM2008}	16474	0.87	0.75	-0.45	9.95	2.86	2.26	-2.92	63.55	1.93	-3.92	61.61	1.99	2.01	1.40	2.69
FABDEM _{MDT}	14603	0.86	0.75	-0.45	9.95	1.27	1.03	-1.51	32.19	1.10	-5.92	28.25	0.41	0.61	0.23	1.08
FABDEM _{EGM2008}	16336	0.86	0.75	-0.45	9.95	2.44	2.18	-0.92	45.56	1.26	-4.00	43.62	1.58	1.59	1.37	1.93
CoastalDEM v2.1 _{MDT}	18954	0.81	0.67	-1.06	9.95	0.75	0.78	-2.46	38.90	1.15	-5.89	36.45	-0.07	0.82	-0.02	1.08
CoastalDEM v2.1 _{EGM96}	18933	0.81	0.67	-1.06	9.95	2.02	2.00	-1.15	53.92	1.23	-6.66	51.47	1.21	1.36	1.28	1.64
GLL-DTM v2 _{MDT(this study)}	17346	0.76	0.66	-0.45	9.95	0.81	0.75	-0.51	7.02	0.55	-8.47	4.12	0.05	0.33	0.09	0.46
GLL-DTM v2 _{MDT(original)}	17354	0.76	0.66	-0.45	7.98	0.95	0.89	-0.75	7.19	0.68	-7.51	4.19	0.19	0.42	0.26	0.55
DeltaDTM v1 _{MDT}	14055	0.86	0.75	-0.45	7.98	0.75	0.68	-1.88	6.77	0.61	-7.35	4.71	-0.11	0.36	-0.07	0.52
DeltaDTM v1 _{EGM2008}	16479	0.86	0.75	-0.45	9.95	1.93	1.84	-0.98	9.77	0.70	-7.09	7.20	1.07	1.11	1.11	1.21
DeltaDTM v1.1 _{MDT}	16459	0.86	0.75	-0.45	9.95	0.63	0.53	-3.55	28.95	0.76	-8.60	27.01	-0.24	0.40	-0.19	0.64
DeltaDTM v1.1 _{EGM2008}	16459	0.86	0.75	-0.45	9.95	1.81	1.70	-2.32	30.00	0.77	-7.50	28.06	0.94	0.99	1.00	1.11

Supplementary Table 2. Performance of local and global DEMs in the Vietnamese Mekong Delta validated by local point elevations ≤ 10 m for versions referenced to mean dynamic topography (MDT) and their original vertical reference. N – number of spot heights in the study area, with no-data values excluded for each DEM, respectively; Mean spot – mean point elevation in the study area; Median spot – median point elevation in the study area; Min. spot – minimum point elevation in the study area; Max. spot – maximum point elevation in the study area; Mean DEM – mean DEM elevation in the study area; Median DEM – median DEM elevation in the study area; Min. DEM – minimum DEM elevation in the study area; Max. DEM – maximum DEM elevation in the study area; σ DEM – standard deviation of DEM elevation in the study area; HR – height residual; MAE – mean absolute error; RMSE – root mean square error.

Converting vertical datum to actual continuous local sea level



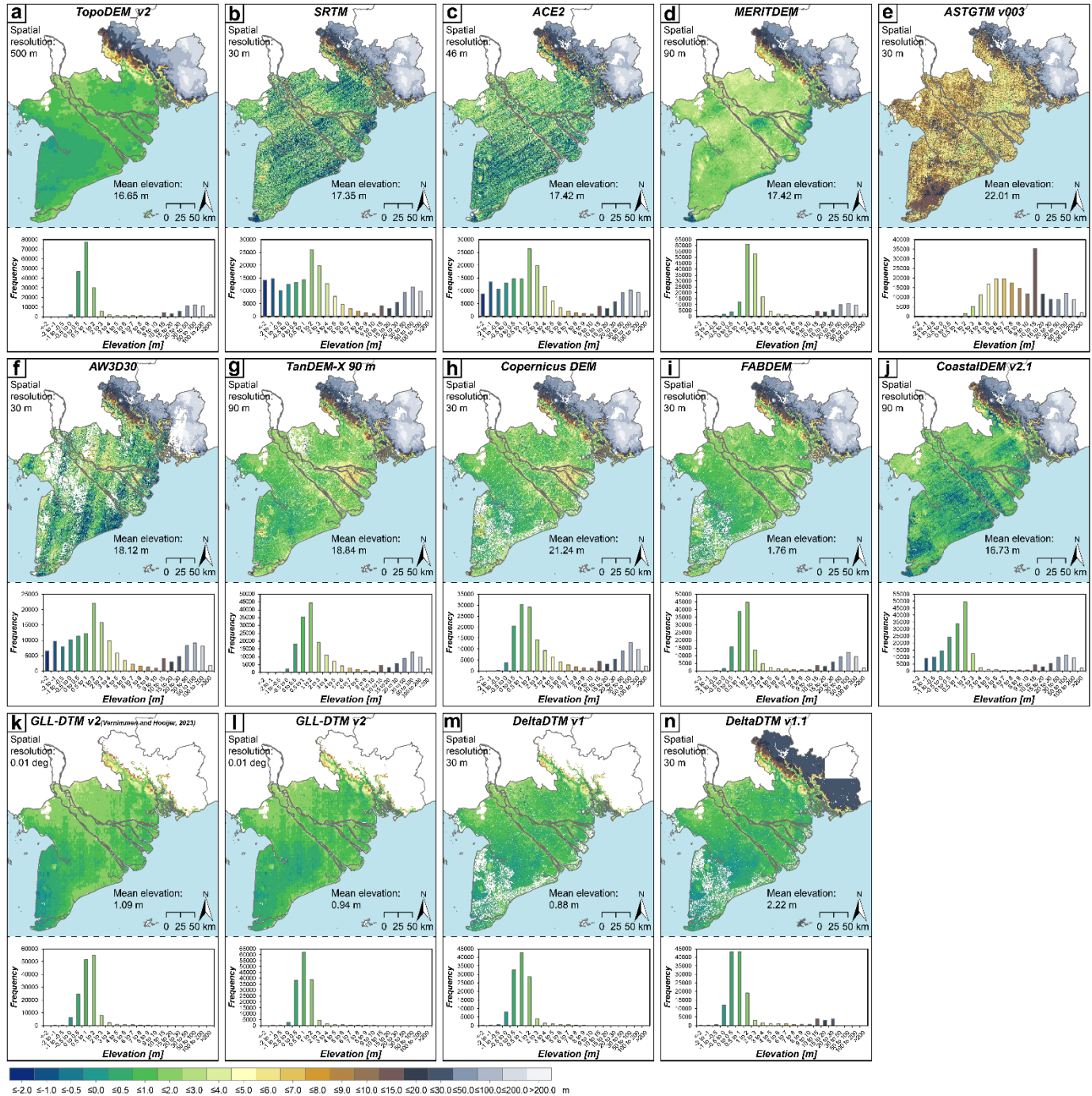
Supplementary Figure 1. Offsets between commonly used geoid models (EGM96 (a); EGM2008 (b)) as well as an example of incomplete datum conversion (c) and local mean sea level as indicated by mean dynamic topography of Jousset et al.¹ in the Vietnamese Mekong Delta. The residual error arising from incomplete datum conversion was calculated for the example of GLL-DTM v2².

Vertical datum	N	Mean offset (m)	Median offset (m)	MAE (m)	RMSE (m)	Min. offset (m)	Max. offset (m)	σ (m)
EGM96	216050	1.32	1.36	1.32	1.34	0.77	1.78	0.25
EGM2008	216050	1.17	1.18	1.17	1.18	0.65	1.63	0.16
Incomplete datum conversion	149890	0.16	0.21	0.26	0.30	-0.39	0.66	0.25

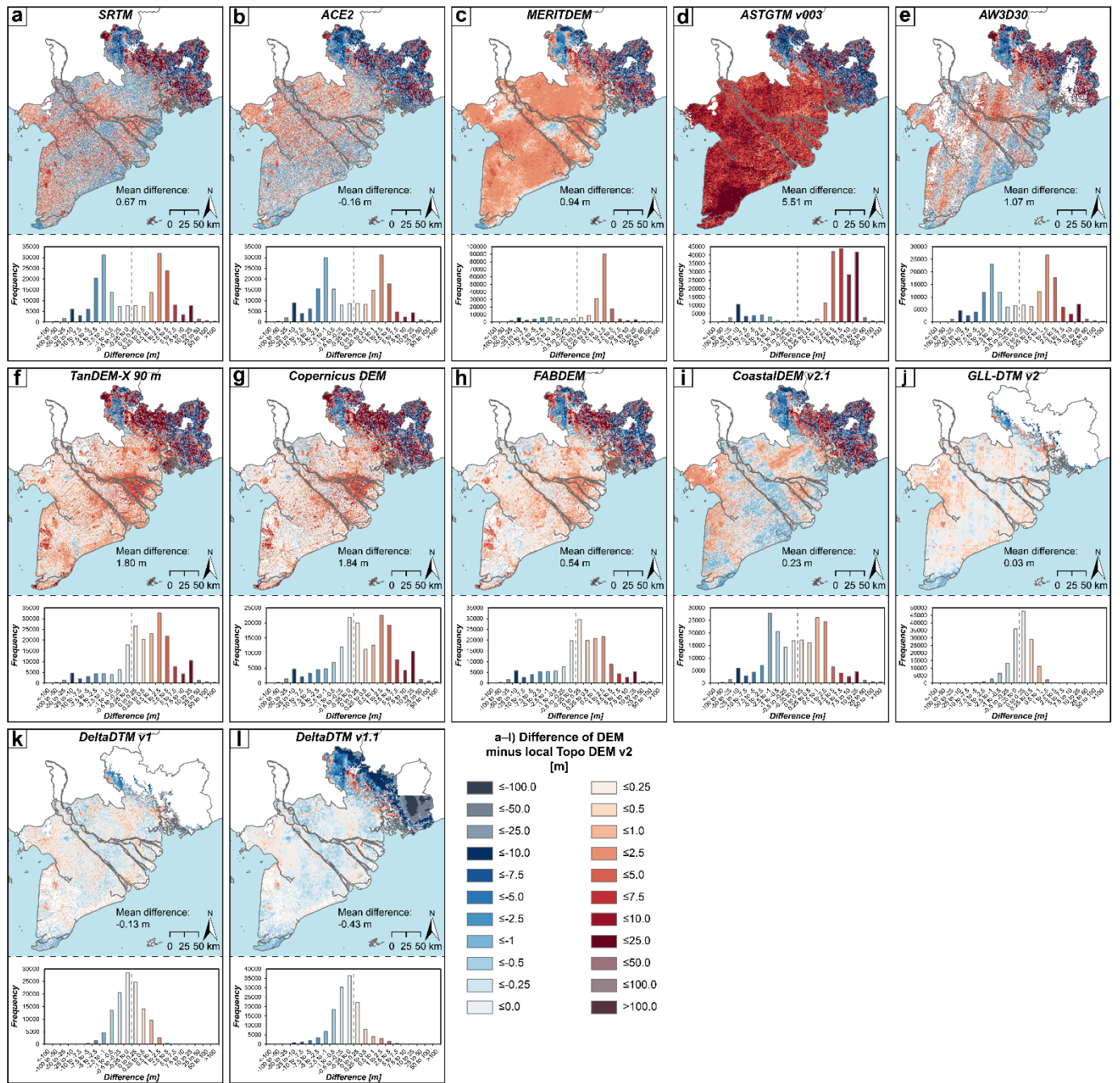
Supplementary Table 3. Offsets between commonly used geoid models (EGM96 (a); EGM2008 (b)) as well as an example of incomplete datum conversion (c) and local mean sea level as indicated by mean dynamic topography of Jousset et al.¹ in the Vietnamese Mekong Delta. The residual error arising from incomplete datum conversion was calculated for the example of GLL-DTM v2².

Performance of digital elevation models in the Vietnamese Mekong Delta and its adjacent provinces

Which one is the best? – On the local validation of global satellite-based digital elevation models: Comparison with local topographical digital elevation model



Supplementary Figure 2. Digital elevation models for the Vietnamese Mekong Delta and its adjacent provinces, all referenced to actual, local continuous mean sea level as indicated by mean dynamic topography of Jousset et al.¹.



Supplementary Figure 3. Height residuals of DEMs referenced to mean sea level compared to TopoDEM_v2 for the Vietnamese Mekong Delta and its adjacent provinces.

DEM	N	Mean DEM (m)	Median DEM (m)	Min. DEM (m)	Max. DEM (m)	σ DEM (m)	Max. negative HR (m)	Max. positive HR (m)	Mean error (m)	MAE (m)	Median error (m)	RMSE (m)	Difference in RMSE (m)	Discrepancy (%)
TopoDEM_v2	219365	16.65	0.91	-0.65	268.65	38.64								
SRTM _{MDT}	203572	17.35	1.86	-6.95	922.24	42.75	-192.81	665.65	0.67	4.34	0.14	12.16	0.11	0.9
SRTM _{EGM86}	205265	18.51	3.00	-7.00	924.00	42.63	-190.72	667.41	1.97	4.63	1.39	12.27		
ACE2 _{MDT}	192353	17.42	1.77	-6.96	869.17	42.86	-166.59	620.86	-0.16	4.22	-0.06	12.28	0.04	0.4
ACE2 _{EGM86}	192702	18.71	3.10	-7.00	870.88	42.84	-164.94	622.57	1.16	4.47	1.21	12.32		
MERITDEM _{MDT}	205967	17.42	2.35	-5.13	936.53	40.99	-183.97	679.93	0.94	3.57	1.20	11.42	0.19	1.6
MERITDEM _{EGM86}	205968	18.74	3.70	-3.87	938.24	41.01	-182.30	681.64	2.26	4.46	2.48	11.60		
ASTGTM v003 _{MDT}	205492	22.01	8.74	-1.46	916.55	39.57	-202.94	659.95	5.51	9.05	5.80	14.60	0.53	3.5
ASTGTM v003 _{EGM86}	205492	23.33	10.00	0.00	918.00	39.58	-201.72	661.41	6.82	9.96	7.09	15.12		
AW3D30 _{MDT}	159639	18.12	2.00	-6.97	715.51	42.40	-158.80	467.18	1.07	4.33	0.29	11.11	0.20	1.7
AW3D30 _{EGM86}	160522	19.34	3.00	-7.00	717.00	42.33	-157.11	468.67	2.38	4.73	1.58	11.30		
TanDEM-X _{MDT}	197363	18.84	1.92	-6.12	1112.77	43.04	-189.93	1039.27	1.80	3.93	0.56	12.52	0.27	2.1
TanDEM-X _{EGM86}	197403	20.15	3.24	-6.53	1113.96	43.06	-188.27	1040.46	3.12	4.88	1.84	12.78		
Copernicus DEM _{MDT}	171963	21.40	2.10	-5.05	909.07	45.62	-186.97	652.48	1.84	4.38	0.33	13.20	0.21	1.6
Copernicus DEM _{EGM2008}	171963	22.41	3.32	-3.85	910.38	45.54	-185.36	653.79	3.01	5.15	1.53	13.41		
FABDEM _{MDT}	172376	19.95	1.51	-2.28	868.39	44.04	-186.92	611.79	0.54	3.54	0.24	12.09	0.59	4.7
FABDEM _{EGM2008}	171087	21.21	2.71	-1.72	922.47	44.21	-202.82	665.87	1.72	4.46	1.39	12.68		
CoastalDEM v2.1 _{MDT}	205653	16.73	1.19	-4.76	937.95	42.32	-208.22	681.36	0.23	3.31	0.01	11.85	0.10	0.9
CoastalDEM v2.1 _{EGM86}	205655	18.05	2.45	-6.33	939.66	42.34	-206.56	683.07	1.55	3.77	1.31	11.96		
GLL-DTM v2 _{MDT (this study)}	150580	0.94	0.79	-1.62	9.61	0.88	-9.29	6.29	0.03	0.34	0.08	0.63	0.04	6.1
GLL-DTM v2 _{MDT (original)}	150982	1.09	0.94	-1.55	9.90	0.99	-8.80	6.36	0.18	0.44	0.25	0.68		
DeltaDTM v1 _{MDT}	120367	0.88	0.78	-3.11	8.91	0.97	-9.44	7.43	-0.13	0.45	-0.08	0.79	0.52	39.7
DeltaDTM v1 _{EGM2008}	125276	2.06	1.88	-1.55	9.99	0.99	-8.10	9.03	1.06	1.17	1.11	1.30		
DeltaDTM v1.1 _{MDT}	139211	2.22	0.62	-5.11	29.15	5.00	-24.95	28.45	-0.43	0.79	-0.21	1.88	0.10	5.2
DeltaDTM v1.1 _{EGM2008}	139211	3.42	1.79	-4.44	30.00	5.03	-23.87	29.30	0.78	1.33	0.99	1.99		

Supplementary Table 4. Performance of local and global DEMs in the Vietnamese Mekong Delta and its adjacent provinces validated by the local TopoDEM_v2 and DEM-specific vertical datum offsets quantified as differences in RMSE and discrepancies from RMSE of DEMs referenced to mean dynamic topography (MDT). The statistics were extracted from DEMs masked for water bodies and outcrops and resampled to 500 m $\times$ 500 m spatial resolution. N – number of grid cells in the study area, with no-data values excluded for each DEM, respectively; Mean DEM – mean DEM elevation in the study area; Median DEM – median DEM elevation in the study area; Min. DEM – minimum DEM elevation in the study area; Max. DEM – maximum DEM elevation in the study area; σ DEM – standard deviation of DEM elevation in the study area; HR – height residual; MAE – mean absolute error; RMSE – root mean square error.

Which one is the best? – On the local validation of global satellite-based digital elevation model: Comparison with local point elevations

DEM	N	Mean spot (m)	Median spot (m)	Min. spot (m)	Max. spot (m)	Mean DEM (m)	Median DEM (m)	Min. DEM (m)	Max. DEM (m)	σ DEM (m)	Max. negative HR (m)	Max. positive HR (m)	Mean error (m)	MAE (m)	Median error (m)	RMSE (m)
TopoDEM_v2	27032	14.51	0.95	-1.06	250.00	14.34	0.92	-0.32	254.65	34.73	-124.55	84.10	-0.17	1.35	0.01	5.08
SRTM _{MDT}	27242	14.44	0.95	-1.06	250.00	14.86	1.75	-6.75	771.08	38.51	-211.19	521.10	0.42	3.66	0.07	11.63
SRTM _{EGM96}	27385	14.37	0.95	-1.06	250.00	16.08	3.00	-6.72	772.78	38.45	-209.52	522.81	1.71	3.93	1.34	11.73
ACE2 _{MDT}	26129	15.00	0.95	-1.06	250.00	14.72	1.57	-6.85	775.88	38.87	-172.74	525.90	-0.28	3.27	-0.25	11.49
ACE2 _{EGM96}	26165	14.98	0.95	-1.06	250.00	16.03	2.89	-6.70	777.59	38.86	-171.08	527.61	1.05	3.44	1.03	11.53
MERITDEM _{MDT}	27283	14.35	0.95	-1.06	250.00	15.14	2.31	-5.50	786.97	37.28	-210.40	537.00	0.79	2.95	1.14	11.45
MERITDEM _{EGM96}	27284	14.35	0.95	-1.06	250.00	16.47	3.68	-4.17	788.68	37.29	-208.73	538.70	2.12	3.86	2.42	11.61
ASTGTM v003 _{MDT}	27393	14.34	0.95	-0.45	250.00	19.81	8.62	-1.23	789.84	35.95	-226.02	539.87	5.47	8.40	5.69	14.34
ASTGTM v003 _{EGM96}	27393	14.34	0.95	-0.45	250.00	21.14	9.95	0.00	791.55	35.95	-224.35	541.57	6.80	9.33	7.00	14.87
AW3D30 _{MDT}	23189	13.56	0.95	-1.06	250.00	14.23	1.89	-6.27	721.66	35.27	-115.68	471.68	0.67	3.43	0.30	9.27
AW3D30 _{EGM96}	23272	13.52	0.95	-1.06	250.00	15.50	3.15	-6.97	723.36	35.25	-113.91	473.39	1.98	3.84	1.59	9.45
TanDEM-X _{MDT}	26439	14.74	0.95	-1.06	250.00	16.41	1.82	-5.40	779.34	39.11	-209.26	529.36	1.66	3.25	0.51	11.94
TanDEM-X _{EGM96}	26444	14.74	0.95	-1.06	250.00	17.73	3.16	-3.79	781.05	39.13	-207.60	531.07	2.98	4.23	1.81	12.20
Copernicus DEM _{MDT}	24642	15.81	0.95	-0.45	250.00	17.38	1.87	-4.15	770.62	40.13	-216.94	520.65	1.57	3.47	0.32	12.37
Copernicus DEM _{EGM2008}	24642	15.81	0.95	-0.45	250.00	18.56	3.08	-2.92	771.93	40.06	-215.33	521.95	2.75	4.25	1.52	12.58
FABDEM _{MDT}	22263	16.91	0.96	-0.45	250.00	17.17	1.48	-0.97	743.02	39.55	-205.50	493.04	0.26	2.87	0.23	11.74
FABDEM _{EGM2008}	24489	15.91	0.95	-0.45	250.00	17.49	2.65	-0.92	781.64	39.01	-220.48	531.67	1.58	3.61	1.37	12.22
CoastalDEM v2.1 _{MDT}	27262	14.36	0.95	-1.06	250.00	14.29	1.21	-4.08	782.29	38.07	-226.40	532.32	-0.07	2.78	-0.00	11.77
CoastalDEM v2.1 _{EGM96}	27262	14.36	0.95	-1.06	250.00	15.62	2.48	-2.39	784.00	38.08	-224.74	534.02	1.26	3.22	1.31	11.84
GLL-DTM v2 _{MDT(this study)}	19250	1.00	0.68	-0.45	9.99	0.97	0.79	-1.78	9.61	0.96	-9.39	6.10	-0.02	0.45	0.08	0.83
GLL-DTM v2 _{MDT(original)}	19311	0.99	0.68	-0.45	9.99	1.14	0.95	-1.40	9.88	1.07	-8.90	6.55	0.14	0.53	0.25	0.84
DeltaDTM v1 _{MDT}	15681	1.12	0.78	-0.45	9.99	0.93	0.72	-1.43	8.44	1.02	-8.94	4.99	-0.18	0.48	-0.07	0.86
DeltaDTM v1 _{EGM2008}	18704	1.13	0.78	-0.45	9.99	2.15	1.90	-0.98	9.87	1.16	-7.58	7.65	1.02	1.18	1.10	1.35
DeltaDTM v1.1 _{MDT}	20674	2.79	0.87	-0.45	29.99	2.31	0.64	-3.55	29.09	5.06	-27.47	26.45	-0.48	0.83	-0.22	1.84
DeltaDTM v1.1 _{EGM2008}	20674	2.79	0.87	-0.45	29.99	3.51	1.82	-2.32	30.00	5.09	-26.39	28.02	0.73	1.30	0.98	1.91

Supplementary Table 5. Performance of local and global DEMs in the Vietnamese Mekong Delta and its adjacent provinces validated by local point elevations for versions referenced to mean dynamic topography (MDT) and their original vertical reference. N – number of spot heights in the study area, with no-data values excluded for each DEM, respectively; Mean spot – mean point elevation in the study area; Median spot – median point elevation in the study area; Min. spot – minimum point elevation in the study area; Max. spot – maximum point elevation in the study area; Mean DEM – mean DEM elevation in the study area; Median DEM – median DEM elevation in the study area; Min. DEM – minimum DEM elevation in the study area; Max. DEM – maximum DEM elevation in the study area; σ DEM – standard deviation of DEM elevation in the study area; HR – height residual; MAE – mean absolute error; RMSE – root mean square error.

Discussion

Year	Extraction-induced land subsidence (cm/yr)	Sea-level change (cm/yr)
2000	0.56	0.36
2001	0.58	0.36
2002	0.62	0.36
2003	0.68	0.36
2004	0.70	0.36
2005	0.73	0.36
2006	0.74	0.36
2007	0.76	0.36
<i>Total (2000–2007)</i>	<i>5.36</i>	<i>2.88</i>
2008	0.78	0.36
2009	0.79	0.36
2010	0.84	0.36
2011	0.84	0.45
2012	0.85	0.45
2013	0.86	0.45
2014	0.86	0.45
2015	0.87	0.45
2016	0.88	0.45
2017	0.88	0.45
2018	0.89	0.45
2019	0.89	0.45
2020	0.89	0.45
2021	0.89	0.49
2022	0.89	0.49
2023	0.89	0.49
2024	0.89	0.49
2025	0.89	0.49
<i>Total (2008–2025)</i>	<i>15.59</i>	<i>8.03</i>

Supplementary Table 6. Simulated, non-linear, extraction-induced land subsidence^{3,4} (B1 scenario of Minderhoud et al.⁴), and annual rates of local, delta-average sea-level rise estimated from PSMSL data of Vung Tau tide-gauge observations (1979–2010)⁵ and IPCC AR6 total rates of sea-level change^{6–8} used to obtain tentative estimates of non-linear impact of elevation change due to vertical land motion (e.g. extraction-induced land subsidence) and sea-level change affecting DEM actuality.

References

1. Jousset, S., Mulet, S., Greiner, E., Wilkin, J., Vidar, L., Dibarboure, G. & Picot, N. New Global Mean Dynamic Topography CNES-CLS-22 Combining Drifters, Hydrological Profiles and High Frequency Radar Data. *ESS Open Archive*, DOI: <https://doi.org/10.22541/essoar.170158328.85804859/v2> (2023).
2. Vernimmen, R. & Hooijer, A. New LiDAR-based elevation model shows greatest increase in global coastal exposure to flooding to be caused by early-stage sea-level rise. *Earth's Future* **11**(1), e2022EF002880, DOI: <https://doi.org/10.1029/2022EF002880> (2023).
3. Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H. & Stouthamer, E. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environ. Res. Lett.* **12**(6), 064006, DOI: <https://doi.org/10.1088/1748-9326/aa7146> (2017).
4. Minderhoud, P. S. J., Middelkoop, H., Erkens, G. & Stouthamer, E. Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environ. Res. Commun.* **2**(1), 011005, DOI: <https://doi.org/10.1088/2515-7620/ab5e21> (2020).
5. Permanent Service for Mean Sea Level (PSMSL). Permanent Service for Mean Sea Level – Tide Gauge Data: Vung Tau, <https://psmsl.org/data/obtaining/stations/1495.php> (2025).
6. Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A. & Yu, Y. Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, 9-1–9-257 (2021).
7. Garner, G. G., Hermans, T., Kopp, R. E., Slangen, A. B. A., Edwards, T. L., Levermann, A., Nowicki, S., Palmer, M. D., Smith, C., Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Yu, Y., Hua, L., Palmer, T. & Pearson, B. IPCC AR6 Sea-Level Rise Projections, Version 20210809, PO.DAAC, CA, USA, Dataset, <https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report> (2021).
8. Garner, G. G., Kopp, R. E., Hermans, T., Slangen, A. B. A., Koubbe, G., Turilli, M., Jha, S., Edwards, T. L., Levermann, A., Nowicki, S., Palmer, M. D. & Smith, C. Framework for Assessing Changes To Sea-level (FACTS), Geoscientific Model Development, *Zenodo* <https://zenodo.org/record/6419954> (2022).