Supplement of Earth Syst. Sci. Data, 13, 2227–2244, 2021
https://doi.org/10.5194/essd-13-2227-2021-supplement

Supplement of

RECOG RL01: correcting GRACE total water storage estimates for global lakes/reservoirs and earthquakes

Simon Deggim et al.

Correspondence to: Simon Deggim (simon.deggim@hcu-hamburg.de) and Annette Eicker (annette.eicker@hcu-hamburg.de)

S1 List of lakes/reservoirs used for the correction RECOG-LR RL01

Lake	Country	Surface area [km^2]
Aberdeen Lake	Canada	1128.2
Achit Lake	Mongolia	296.2
Acude Oros Reservoir	Brazil	61.3
Albert Lake	Uganda	5401.9
Alcantara Reservoir	Spain	45.3
Allegheny Reservoir	United States	41.4
Almanor Lake	United States	104.6
Alvaro Obregón Reservoir	Mexico	74.8
Amadjuak Lake	Canada	3033.7
Angostura Lake	Mexico	566.3
Apoquitaua Lake	Brazil	125.9
Aqqikkol Lake	China	355.6
Argentino Lake	Argentina	1401.9
Argyle Lake	Australia	829.2
Assad Lake	Syria	638.6
Atatürk Lake	Turkey	695.1
Ayakkum Lake	China	575.1
Badajós Lake	Brazil	227.4
Bagre Reservoir	Burkina Faso	167.9
Baikal Lake	Russia	31924.6
Baker Lake	Canada	1780.3
Balaton Lake	Hungary	578.2
Balbina Reservoir	Brazil	2304.8
Balkhash Lake	Kazakhstan	17458.8
Bangweulu Lake	Zambia	2049.1
Bankim Lake	Cameroon	163.9
Barna Reservoir	India	46.6
Berryessa Lake	United States	66.6
Beysehir Lake	Turkey	659.6
Bisalpur Reservoir	India	59.4
Boston Lake	China	999.5
Bratskoe Reservoir	Russia	4810.8
Buchanan Lake	United States	80.5
Buenos Aires Lake	Chile	1848.2
Burdekin Reservoir	Australia	210.5
Buyo Lake	Ivory Coast	508.7
Cabaliana Lake	Brazil	205.1
Caddabassa Lake	Ethiopia	91.6
Caddo Lake	United States	60.3
Cahora Bassa Lake	Mozambique	2047.5
Canyon Ferry Lake	United States	156.5
Carey Lake	Canada	247.9
Caspian Sea	Kazakhstan	378119.3
Cedar Lake	Canada	2817.3
Chad Lake	Chad	19346.6
Chamo Lake	Ethiopia	324.8

Lake	Country	Surface area [km²]
Chandil Dam Reservoir	India	33.6
Chapala Lake	Mexico	1127.3
Chiquita Lake	Argentina	2011.9
Choke Canyon Reservoir	United States	55.1
Churumuco Lake	Mexico	288.0
Claire Lake	Canada	1325.6
Coari Lake	Brazil	646.2
Colville Lake	Canada	433.1
Constance Lake	Germany	516.0
Contwoyto Lake	Canada	1092.5
Cumberland Lake	United States	159.5
CW McConaughy Lake	United States	122.1
Dale Hollow Lake	United States	89.6
Dongting Lake	China	778.7
Dore Lake	Canada	634.4
Dubawnt Lake	Canada	3628.5
Edward Lake	Zaire	2252.5
Elwell Reservoir	United States	61.9
Encoro de Salas Reservoir	Portugal	16.0
Enriquillo Lake	Dominican Republ	259.5
Erepecu Lake	Brazil	628.2
Erie Lake	Canada	25691.0
Eucumbene Lake	Australia	121.4
Eufaula Reservoir	United States	354.9
Fehet Lake	Canada	105.7
Flathead Lake	United States	487.6
Flores Reservoir	Brazil	65.0
Forde Lake	Canada	303.0
Fort Peck Lake	United States	814.2
Francis Case Lake	United States	328.3
Gandhi Sagar Reservoir	India	521.7
Garry Lake	Canada	787.0
Geneva Lake	Switzerland	558.2
Govind Ballabh Pant Sagar Lake	India	415.3
Grande do Curuai Lake	Brazil	381.8
Grandin Lake	Canada	248.5
Grapevine Lake	United States	21. Feb
Great Bear Lake	Canada	30530.1
Great Salt Lake	United States	5965.8
Great Slave Lake	Canada	27816.3
Guarabi Lake	Brazil	196.0
Guri Lake	Venezuela	3661.0
Hardisty Lake	Canada	319.4
Harlan County Lake	United States	50.0
Harry S Truman Reservoir	United States	186.8
Hartwell Lake	United States	189.2
Hebgen Lake	United States	46.5
Hottah Lake	Canada	955.1
Hubbard Creek Reservoir	United States	43.1

Lake	Country	Surface area [km^2]
Hulun Lake	China	2166.5
Huron Lake	Canada	59756.5
Hyargas Lake	Mongolia	1362.7
Ilha Solteira Reservoir	Brazil	1077.3
Ilmen Lake	Russia	951.2
Inder Lake	Kazakhstan	105.8
Issyk Kul Lake	Kyrgyzstan	6258.9
Itaparica Reservoir	Brazil	687.6
Itutinga Reservoir	Brazil	56.3
Izabal Lake	Guatemala	737.6
Jacarei Reservoir	Brazil	38.9
Jurumirim Reservoir	Brazil	373.5
Kabamba Lake	Zaire	178.6
Kabele Lake	Zaire	102.3
Kabwe Lake	Zaire	100.8
Kainji Lake	Nigeria	1034.8
Kajaki Reservoir	Afghanistan	46.1
Kamilukuak Lake	Canada	672.1
Kaminuriak Lake	Canada	565.4
Kapchagay Reservoir	Kazakhstan	1273.0
Kara Bogaz Gol Lake	Turkmenistan	918.9
Karakaya Baraji Reservoir	Turkey	194.9
Kariba Lake	Zimbabwe	5276.2
Keller Lake	Canada	390.7
Khantaiskoye Lake	Russia	1441.7
Khuvsgul Lake	Mongolia	2741.4
Kisale Lake	Zaire	277.8
Kivu Lake	Zaire	2370.7
Koosa järv Lake	Russia	3552.8
Kossou Lake	Ivory Coast	500.3
Krasnoyarskoye Reservoir	Russia	1629.6
Kremenchuk Reservoir	Ukraine	1849.1
Kusai Lake	China	255.7
Kuybyshev Reservoir	Russia	5003.3
Kyoga Lake	Uganda	1727.7
La Grande Reservoir	Canada	2572.6
Lac Changalele Reservoir	Congo (DRC)	179.6
Ladoga Lake	Russia	17539.1
Lagdo Lake	Cameroon	622.6
Lagoa da Funda Lake	Angola	23. Jan
Lake of the Woods	Canada	4167.7
Langa Co Lake	China	277.5
Lesser Slave Lake	Canada	1152.0
Llanquihue Lake	Chile	865.9
Loups Marins Lake	Canada	510.6
Luther Lake	Canada	59756.5
Mai Ndombe Lake	Zaire	1954.9
Maithan Dam Reservoir	India	76.1
Malawi Lake	Malawi	29251.5

Lake	Country	Surface area [km^2]
Mallery Lake	Canada	444.7
Managua Lake	Nicaragua	1023.8
Manso Reservoir	Brazil	49.4
Marfil Lake	Bolivia	104.9
Massingir Lake	Mozambique	118.9
Maunoir Lake	Canada	341.8
Mead Lake	United States	581.0
Meredith Lake	United States	35.0
Michigan Lake	United States	57399.4
Mille Lacs Lake	United States	496.3
Mosul Dam Lake	Iraq	346.9
Murray Lake	United States	180.8
Musters Lake	Argentina	407.8
Mweru Mantipa Lake	Zambia	110.1
Mweru Lake	Zambia	4944.8
Nam Co Lake	China	1933.6
Nam Ngum Lake	Laos	443.8
Nasser Lake	Egypt	5383.3
Nettiling Lake	Canada	5064.7
Netzahualcóyotl Lake	Mexico	292.0
Ngangze Lake	China	411.3
Nicaragua Lake	Nicaragua	7851.5
Nipigon Lake	Canada	4476.9
Norfolk Lake	United States	79.4
Nova Ponte Reservoir	Brazil	237.3
Novosibirsk Reservoir	Russia	1024.2
Nowleye Lake	Canada	275.3
Nueltin Lake	Canada	2011.9
Nzilo Reservoir	Zaire	266.7
O. H. Ivie Reservoir	United States	47.1
Oahe Lake	United States	1092.6
Okeechobee Lake	United States	1436.8
Onega Lake	Russia	9773.9
Ontario Lake	Canada	19328.9
Oro Lake	Mali	110.3
Panchet Dam Reservoir	India	47.9
Peipus Lake	Russia	3552.8
Pires Ferreira Reservoir	Brazil	45.0
Poço da Cruz Reservoir	Brazil	3.0
Poopó Lake	Bolivia	1262.9
Pórisvatn Lake	Iceland	66.4
Powell Lake	United States	647.8
Poyang Lake	China	2108.1
Qadisiyah Lake	Iraq	339.2
Qarun Lake	Egypt	232.7
Qinghai Lake	China	4449.7
Rajghat Reservoir	India	46.7
Ramganga Reservoir	India	47.2
Ranco Lake	Chile	441.9

Lake	Country	Surface area [km^2]
Rathbun Lake	United States	50.6
Ray Roberts Reservoir	United States	68.7
Razazza Lake	Iraq	1330.3
Reindeer Lake	Canada	5596.6
Richland Chambers Reservoir	United States	156.5
Robert Bourassa Reservoir	Canada	3107.6
Rockinghorse Lake	Canada	221.5
Roseires Reservoir	Sudan	225.2
Rukwa Lake	Tanzania	1965.8
Rweru Lake	Burundi	102.4
Rybinsk Reservoir	Russia	3926.6
Saint Jean Lake	Canada	1106.2
Sakakawea Lake	United States	1126.8
Salton Sea	United States	929.0
Sam Rayburn Reservoir	United States	380.1
Sao Geronimo Lake	Brazil	104.7
Saratovsk Reservoir	Russia	1073.4
Sarygamysh Lake	Turkmenistan	752.4
Schultz Lake	Canada	418.0
Selingue Reservoir	Mali	335.7
Seminoe Reservoir	United States	57.2
Serra de Mesa Reservoir	Brazil	922.7
Sevan Lake	Armenia	1249.9
Shadehill Reservoir	United States	17. Feb
Shala Lake	Ethiopia	310.5
Siling Co Lake	China	1640.9
Sobradinho Reservoir	Brazil	2614.9
Songhua Lake	China	193.3
South Henrik Lake	Canada	569.6
Stockton Lake	United States	96.4
Strom Thurmond Lake	United States	131.4
Sudd Swamps	Sudan	161.3
Superior Lake	Canada	81935.7
Table Rock Lake	United States	118.1
Tai Hu Lake	China	2398.5
Takijuq Lake	Canada	1013.9
Tana Lake	Ethiopia	3034.7
Tanganyika Lake	Zaire	32820.5
Tangra Yumco Lake	China	828.2
Tarbela Reservoir	Pakistan	208.4
Taupo Lake	New Zealand	600.5
Tawakoni Lake	United States	137.7
Tebesjuak Lake	Canada	488.6
Tehek Lake	Canada	491.1
Tengiz Lake	Kazakhstan	1382.6
Teshekpuk Lake	United States	834.9
Tharthar Lake	Iraq	1698.8
Titicaca Lake	Peru	8270.6
Toba Lake	Indonesia	1133.8

Lake	**Country**	**Surface area [km^2]**
Todos los Santos Lake	Chile	175.6
Toktogul Reservoir	Kyrgyzstan	223.5
Toledo Bend Reservoir	United States	599.6
Tres Irmaos Reservoir	Brazil	591.8
Tschida Lake	United States	10. Apr
Tshchikskoye Lake	Russia	269.2
Tsimlyansk Reservoir	Russia	2242.4
Tucurui Reservoir	Brazil	2349.1
Tulemalu Lake	Canada	656.8
Tumba Lake	Zaire	697.0
Turkana Lake	Kenya	7785.4
Ubinskoye Lake	Russia	433.3
Ukai Reservoir	India	370.2
Ulungur Lake	China	757.5
Unknown Reservoir	India	30.0
Unknown Reservoir	Mexico	134.9
Unknown Target	Mexico	141.4
Upemba Lake	Zaire	573.0
Urmia Lake	Iran	4963.4
Urua Lake	Brazil	196.0
Uvs Lake	Mongolia	3421.5
Van Lake	Turkey	3537.9
Vänern Lake	Sweden	5550.5
Vani Vilasa Sagara Reservoir	India	39.3
Victoria Lake	Tanzania	67075.2
Viedma Lake	Argentina	1047.4
Volta Lake	Ghana	6043.9
Walker Lake	United States	165.5
Wharton Lake	Canada	407.1
Williston Lake	Canada	1654.0
Winnipegosis Lake	Canada	5167.1
Wollaston Lake	Canada	2272.0
Yathkyed Lake	Canada	1320.4
Yellowstone Lake	United States	327.8
Zanzulu Reservoir	Angola	123.1
Zaysan Lake	Kazakhstan	4193.7
Zeyskoye Reservoir	Russia	2234.8
Zhari Namco Lake	China	1004.4
Zimbambo Lake	Zaire	204.7
Ziway Lake	Ethiopia	410.5
Zujar Reservoir	Spain	93.1

S2 Determination of surface water extent

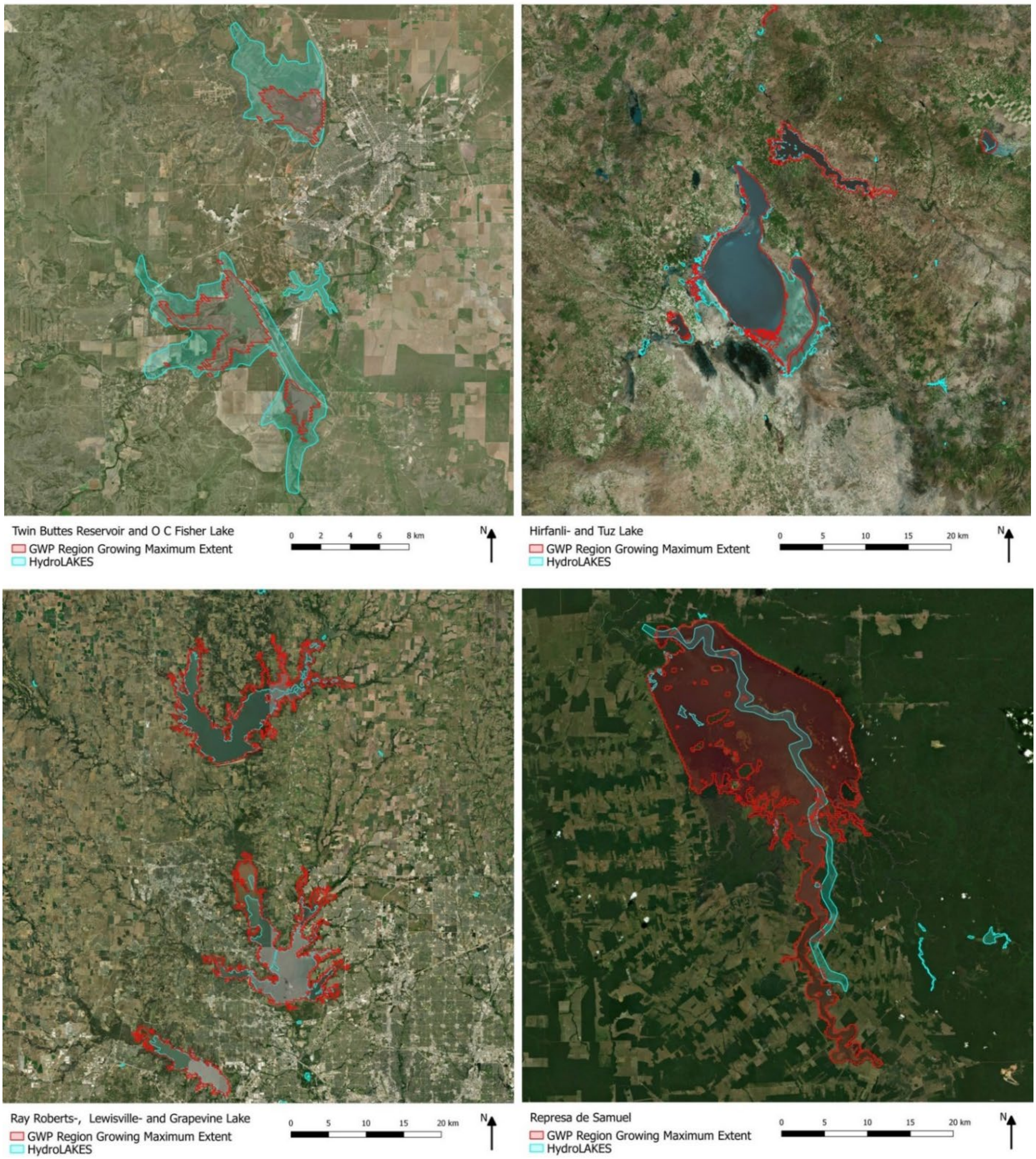

Figure S2: Estimated maximum extent of four lakes with comparison to the HydroLAKES dataset. Examples show the correction of overestimation (top) and underestimation (bottom) of surface water extent by a static approximation (blue). The red GWP shapes are the final shapes used for RECOG-LR. (Background: Bing Maps, © Microsoft)

S3 Seasonal cycle of RECOG-LR

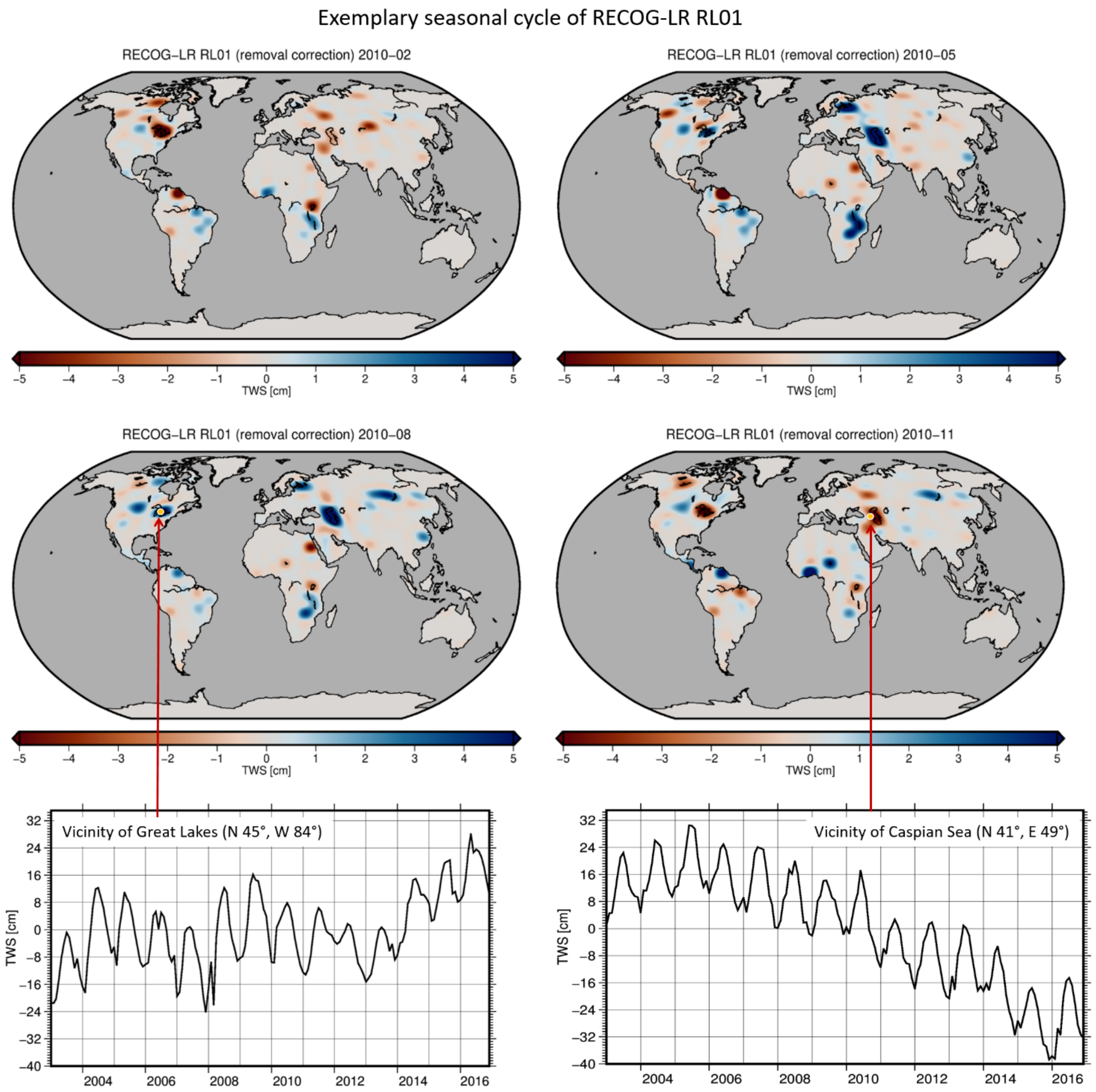

Figure S3: Monthly correction results for February (top left), May (top right), August (middle left) and November (middle right) of 2010. Note that for better visibility of the smaller lakes, the very strong signals (e.g. for the Caspian Sea and the Great Lakes, see time series on bottom row) go beyond the scale of +- 5 cm.

S4 Altimetry time series for the Great Lakes

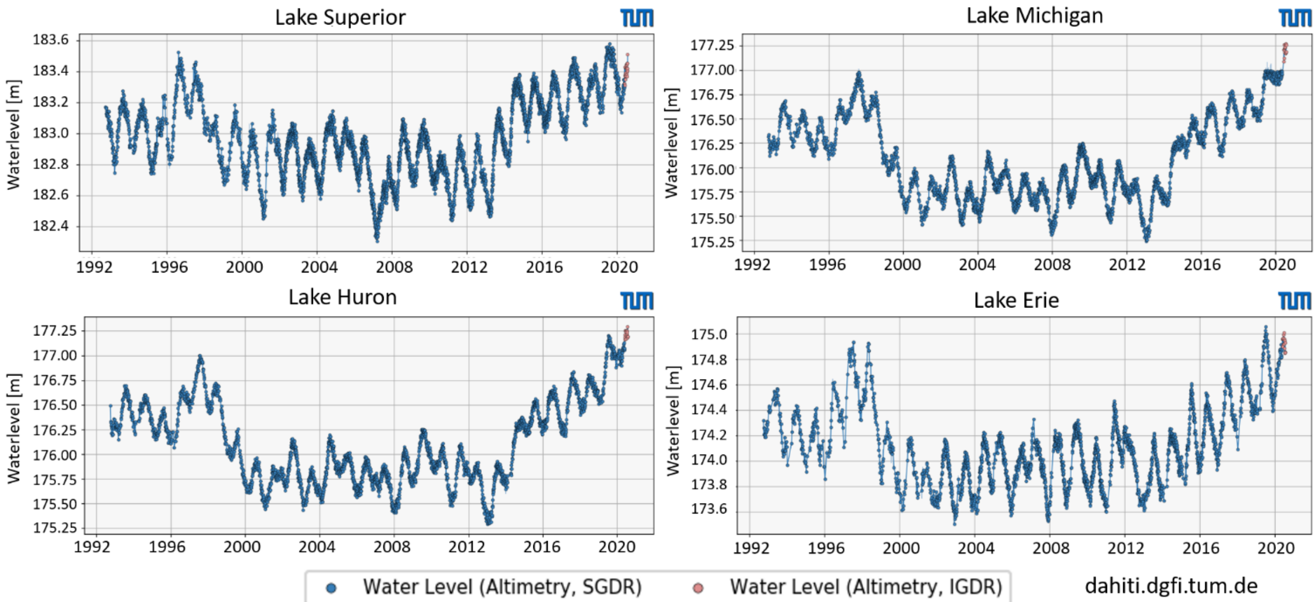

Figure S4: Time series of Great Lakes in North America from the DAHITI database.

S5 Linear trends of Earthquake correction for Sumatra-Andaman earthquake 2004

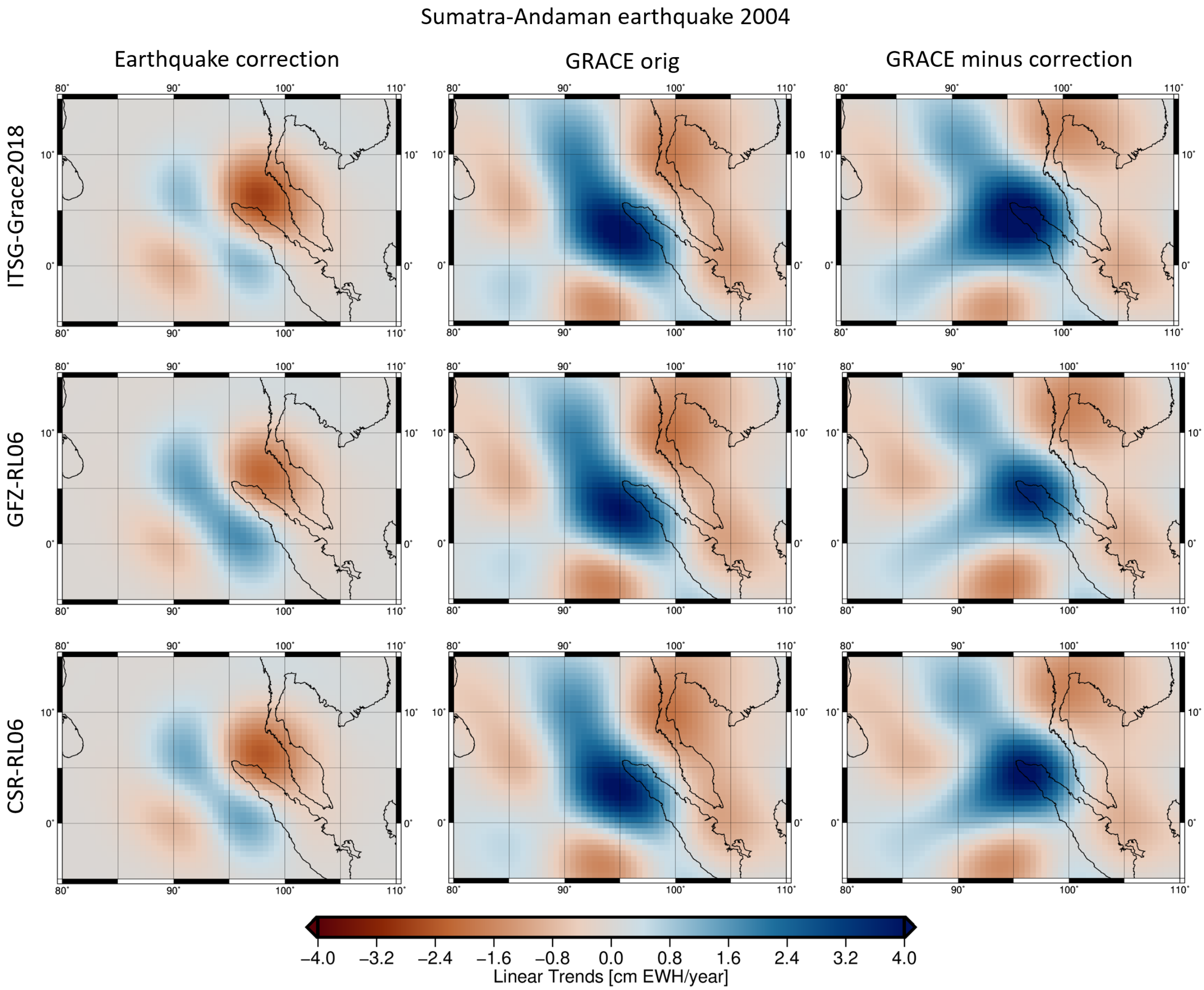

Figure S5: Comparison of linear trends (01/2003 – 12/2016) of the earthquake correction (left), the original (middle) and corrected TWS changes (right) in cm EWH/year for the different GRACE solutions ITSG-Grace2018 (top), GFZ-RL06 (middle) and CSR-RL06 (bottom) of the Sumatra-Andaman earthquake from 2004.

S6 Linear trends of Earthquake correction for Tohoku earthquake 2011

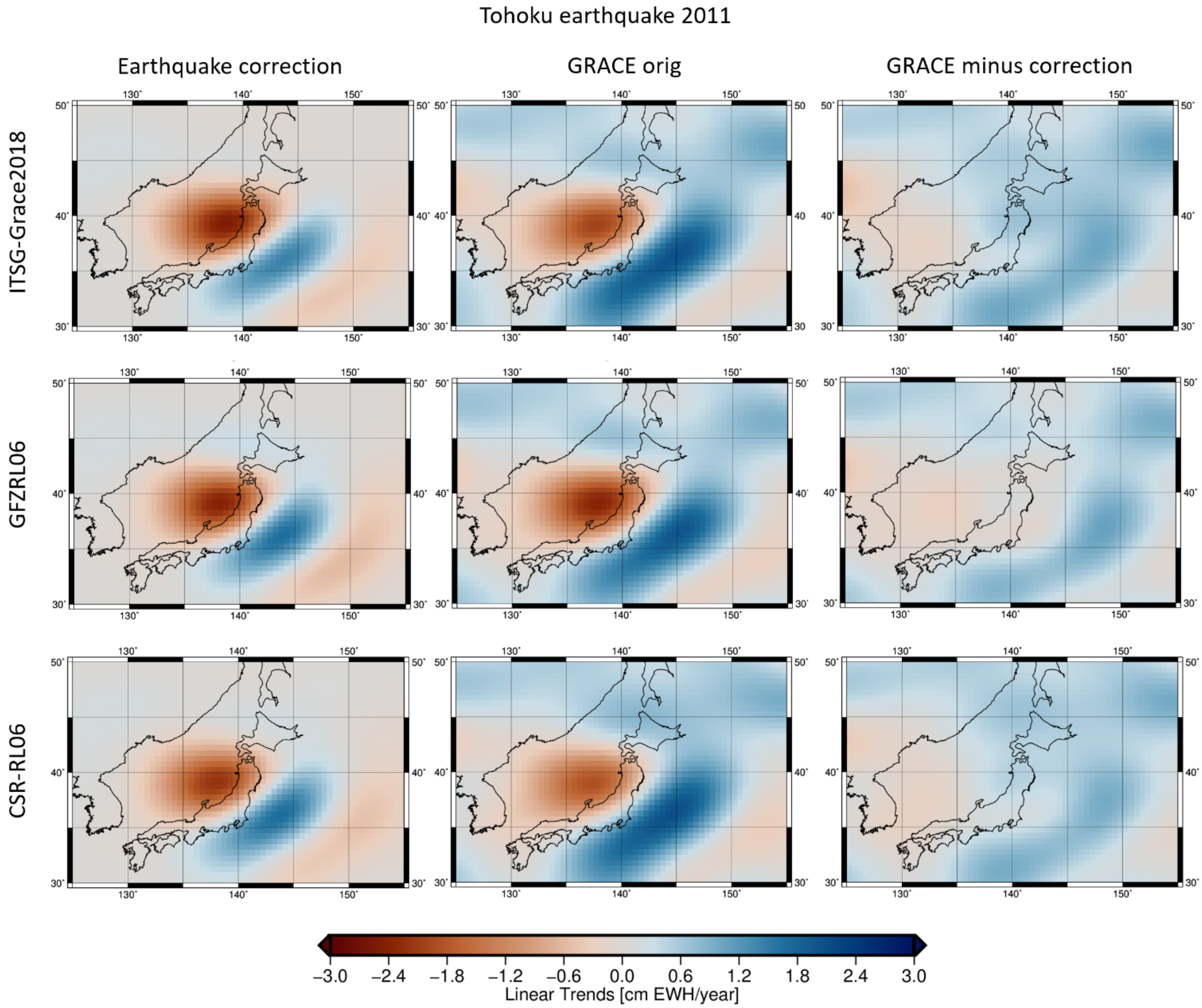

Figure S6: Comparison of linear trends (01/2003 – 12/2016) of the earthquake correction (left), the original (middle) and corrected TWS changes (right) in cm EWH/year for the different GRACE solutions ITSG-Grace2018 (top), GFZ-RL06 (middle) and CSR-RL06 (bottom) of the Tohoku earthquake from 2011.

Figures S5 and S6 show the comparison of the linear trends for the correction, the original and corrected total water storage changes for different GRACE solutions. The ITSG-Grace2018 solution is discussed in more detail in the paper, but the main findings describe that the linear trends in the Sumatra-Andaman regions and the Tohoku region are biased by the earthquake signal. For the Sumatra-Andaman region this led to a medium change in magnitude and spatial pattern, while in Tohoku large differences between the uncorrected and corrected GRACE signal appeared. The linear trends were very close to zero after correcting the GRACE data. The GFZ-RL06 and CSR-RL06 solutions show now that very similar linear trends can be observed when comparing the original data, regardless of the earthquake considered. The earthquake correction can continue these findings. Each solution is in the same magnitude and identifies equal regions that are affected. Therefore, it is very important to correct the GRACE data for earthquakes to avoid misinterpretations in hydrological applications. We provide the earthquake correction RECOG-EQ for all three solutions on Pangaea as described in the paper.

S7 Influence of lake correction RECGO-LR on GRACE trends

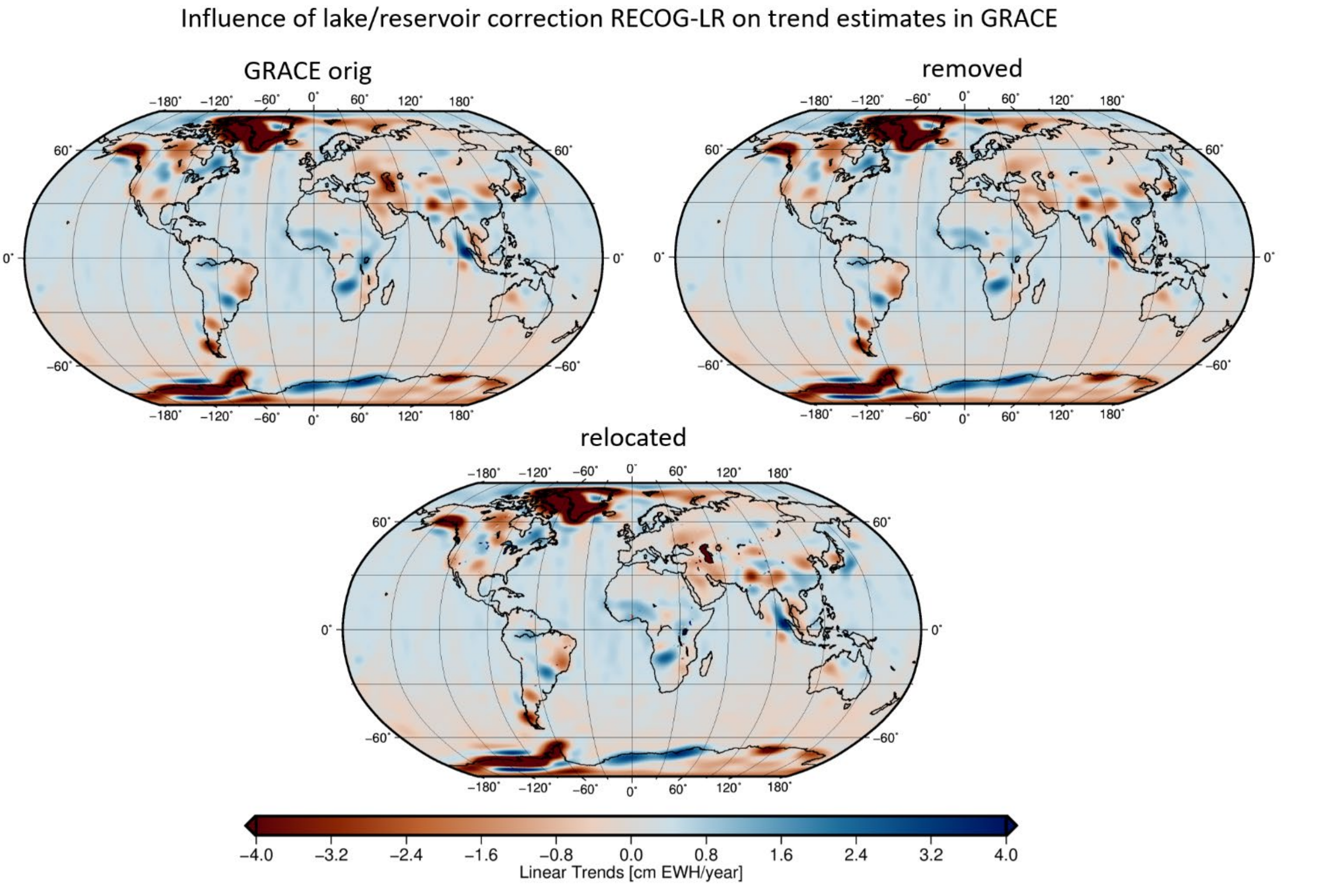

Figure S7: Global map of trends in the original GRACE data (top left), after removing the surface water correction RECOG-LR (top right) and after relocating the altimetry-derived surface water storage to its original location (bottom).

S8 Assimilation of GRACE data into the hydrological model WaterGAP

Assimilation of subbasin-averaged TWSA time series of the original and the RECOG-corrected GRACE dataset was performed into the Water-Global Assessment and Prognosis (WaterGAP; Döll et al. 1999, Müller Schmied et al., 2014) hydrological model. WaterGAP is a global hydrological model simulating ten water compartments (snow, canopy, soil, groundwater, global/local lakes, global/local wetlands, reservoirs, and river) for each grid cell of a global 0.5° x 0.5° grid considering human influences on water resources.

Our assimilation theory follows Eicker et al. (2014) and Schumacher et al. (2015, 2016), but to improve the computation time of the data assimilation we coupled the model with the Parallel Data Assimilation Framework (PDAF; Nerger and Hiller, 2013). Perturbing the calibration parameters of the model as well as temperature and precipitation as forcing data, we generate 30 ensemble members and apply an Ensemble Kalman Filter, which is tuned with a forgetting factor of 0.8 (Evensen, 2003).

During the assimilation of the original and relocated dataset, we update all ten compartments of the WaterGAP, while we do not update the lakes and reservoirs when considering the removed dataset. To enable a fair comparison of the influence of the correction dataset, we use the same propagated error information for both datasets for assimilation.

References:

Döll, P., Kaspar, F., and Alcamo, J.: Computation of global water availability and water use at the scale of large drainage basins, MathematischeGeologie, 4(1), 111-18, 1999.

Eicker, A., Schumacher, M., Kusche, J., Döll, P. and Müller Schmied, H.: Calibration/Data Assimilation Approach for Integrating GRACE Data into the WaterGAP Hydrological Model (WGHM) Using an Ensemble Kalman Filter: First Results, Surv Geophys, 35, 1285-1309, doi:10.1007/s10712-014-9309-8, 2014.

Evensen, G.: The ensemble Kalman filter: Theoretical formulation and practical implementation, Ocean dynamics, 53(4), 343-367, 2003.

Nerger, L., and Hiller, W.: Software for ensemble-based data assimilation systems – Implementation strategies and scalability, Computers & Geosciences, 55, 110-118, 2013.

Schumacher, M., Eicker, A., Kusche, J., Schmied, H. M., and Döll, P.: Covariance analysis and sensitivity studies for GRACE assimilation into WGHM, IAG 150 Years, 241-247, Springer, Cham, 2015.

Schumacher, M., Kusche, J., and Döll, P.: A systematic impact assessment of GRACE error correlation on data assimilation in hydrological models, Journal of Geodesy, 90(6), 537-559, 2016.

S9 GRACE TWSA time series at epicentres of earthquakes

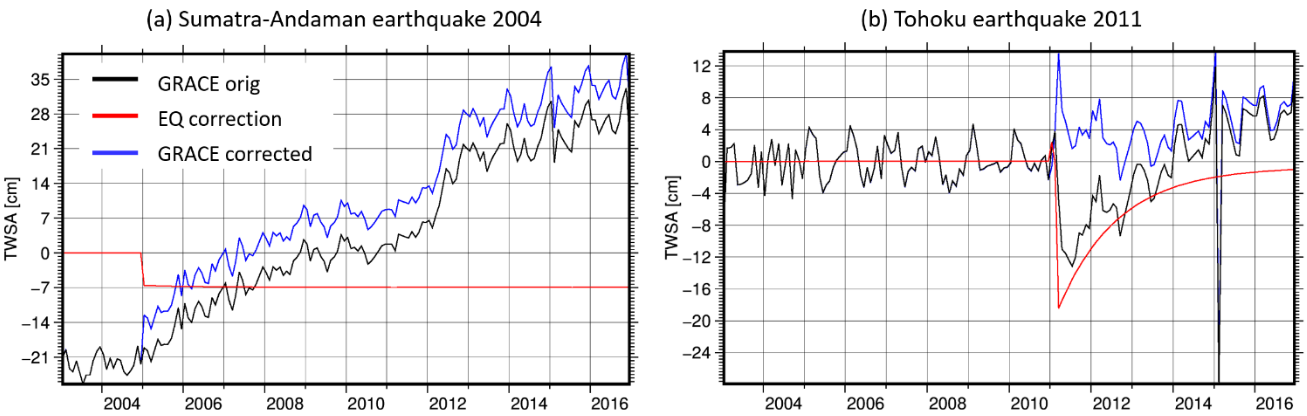

Figure S9: GRACE TWSA at the chosen grid that is closest to the epicenter of the (a) Sumatra-Andaman earthquake in 2004 (epicenter location: 3.32° N, 95.85° E, closest to TWSA grid location: 3.25° N, 95.75° E) and the (b) Tohoku earthquake in 2011 (epicenter location: 38.32° N, 142.37° E, closest to TWSA grid location: 38.25° N, 142.25° E) shown for the original (black) and the corrected (blue) GRACE total water storage anomalies earthquake correction.

Figure S9 shows the time series for the GRACE at the closest location to the epicenters for the Sumatra-Andaman earthquake in 2004 and the Tohoku earthquake in 2011. For Sumatra-Andaman the location with 97.75 degrees east and 3.25 degrees north is chosen. The correction (red) shows a clear visible step function, but less influence of a post-seismic relaxation. It is important to understand that the earthquake correction models are fitted to the geoid or gravity anomalies in the space domain, i.e. to gridded representations. Transforming from geoid to TWSA requires spatial smoothing operations such that the temporal evolution of individual grid corrections are overlaid. As a result one cannot expect to see the original relaxation effect as clearly as e.g. in Einarsson et al. (2009).

S10 Vertical surface displacement at ITRF2014 GNSS sites

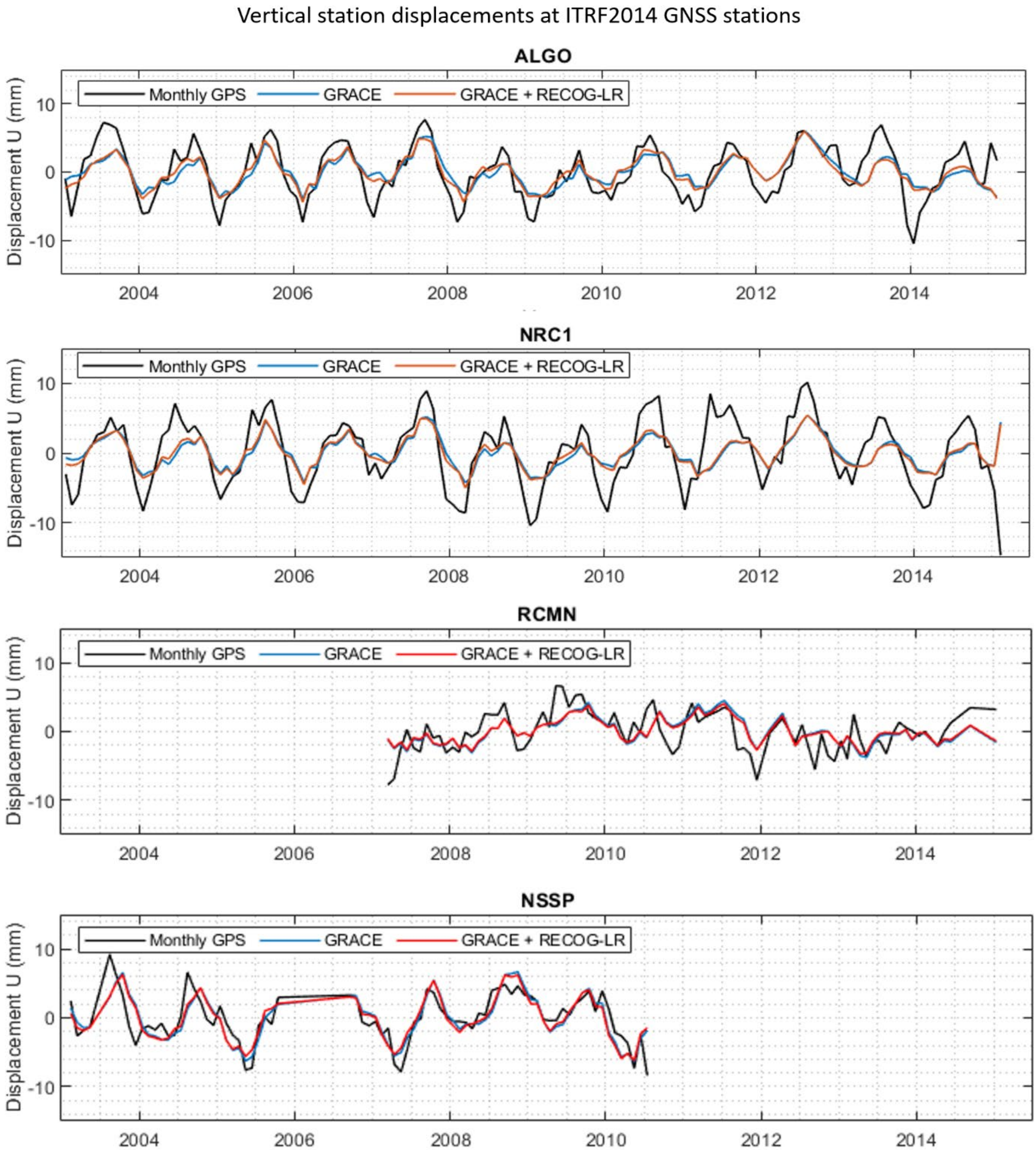

Figure S10: Vertical surface displacement at four ITRF2014 GNSS sites located in the Great Lakes region (ALGO and NRC1), around Lake Victoria (RCMN) and the Caspian Sea (NSSP). The black line shows the GNSS observations and the blue line the surface displacements modelled from the original GRACE time series. The red line illustrates the displacement time series after removing the leakage correction (RECOG-LR RL01) and relocating the altimetry-derived surface water storage change to its original location.