EO-1-2014: New ideas for Earth-relevant space applications
Research and Innovation action

Action acronym:	**EGSIEM**
Action full title:	European Gravity Service for Improved Emergency Management
Grant agreement no:	637010

Deliverable D4.2
Scientific Service Product Report

Date: 22/9/2017

Author(s): UM, YJ, AK

1. Change Record

Name	Author(s)	Date	Document ID
Draft 1	UM, YJ, AK	22/09/2017	D4.2_Scientific_Service
Draft 2			
Draft 3			

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2. Overview of Task 4.2

Work Package 4: Scientific Service, according to the EGSIEM proposal, aims to

- combine the global monthly gravity models from individual ACs (Analysis Centres),
- provide user-friendly Level-3 products, and
- validate the individual and the combined gravity field solutions.

It consists of the following Tasks:

- T4.1: Design and Concept,
- T4.2: Operation, and
- T4.3: External validation.

In T4.2 service operations were performed for the GRACE solutions derived by the EGSIEM ACs in WP2. Monthly solutions up to degree and order 90 (corresponding to the EGSIEM standards) were provided by UBERN (AIUB), GFZ and TU Graz (ITSG). GRGS (CNES) provided monthly solutions up to degree and order 80 that were also included in the combination.

The individual AC's contributions were validated in terms of signal and noise content following the procedures described in Deliverable 4.1. They were also compared to their corresponding predecessors whenever applicable (i.e., EGSIEM-AIUB to AIUB-RL02, EGSIEM-GFZ to GFR-RL05a and EGSIEM ITSG to ITSG-Grace2014) to assess the improvements achieved within WP2. For EGSIEM-GRGS no such comparison was possible because all previous GRGS releases were regularized. ULux did not provide any monthly gravity fields. The results of the internal validation are given in Section 3.

Section 4 is devoted to the combination of the monthly gravity fields. The first combination is performed on solution level applying variance component estimation to derive relative weights representative for the noise levels of the individual contributions. The monthly fields combined on solution level are provided together with the formal errors of the combination for internal use within the EGSIEM project. In a second step the derived weights are applied to the combination on normal equation level and the monthly fields combined on solution level are validated internally corresponding to the validation of the individual contributions in Section 3. External validation of the combined gravity fields is performed in Task 4.3 and described in D4.3.

Finally, the Level-2 monthly gravity fields combined on normal equation level are transformed into user-friendly and pre-filtered grids for hydrological and oceanographic applications. Therefore the combined de-aliasing products are restored and degree 1 spherical harmonic coefficients added to reconstruct full (non-tidal) signal content. Then models of different mass variations are applied and the reduced coefficients are transformed into equivalent water heights. They are finally filtered specifically for the corresponding application and transformed into global grids (see Section 5).

The Level-2 and Level-3 products are visualized by the EGSIEM plotter (WP7, T7.2) and distributed via the EGSIEM webpage (www.egsiem.eu) and ICGEM (icgem.gfz-potsdam.de).

3. Internal validation of the ACs individual contributions

The individual contributions of monthly GRACE GPS + K-band gravity fields of the EGSIEM ACs were prepared within WP2 and are the products of a dedicated processing based on the EGSIEM standards and EGSIEM GPS orbits and clock corrections. All ACs were encouraged to also improve their individual processing strategies within the frame of EGSIEM WP2. The individual contributions are internally validated and then combined in WP4.

We here compare the individual AC's contributions to their precursors, i.e., the corresponding releases of monthly gravity fields publicly available at ICGEM, to illustrate the progress achieved in WP2. All gravity fields are validated for the two test years 2006 and 2007 provided by EGSIEM. The EGSIEM specifications rule out any regularization, in consequence we assume that signal content is preserved and therefore focus on the noise levels of the different gravity fields.

Noise is assessed by the non-seasonal, non-secular variability, i.e., the residuals with respect to a deterministic model of time-variations (furtheron called anomalies). These anomalies can be computed in the spherical harmonic domain, i.e., per spherical harmonic coefficient (SHC), or in the spatial doamain, i.e., per grid cell of global grids of the monthly gravity fields. Both types of anomlies were compared and it was found that in case of a spatial resolution of the global grids that fits the spherical harmonic resolution of the gravity fields both versions of anomalies yield similar results (furtheron all anomalies are computed in the spherical harmonic domain ant then eventually transformed to the spatial domain). The deterministic model of temporal variations needed to define the anomlies was derived based on all time-series available at ICGEM that are not subject to regularization.

In Figure 1 the median of degree amplitudes of anomalies of SHC of the two test years 2006 and 2007 are shown. The degree amplitudes were truncated at order 29. The high order SHC generally are dominated by noise and in most applications, are filtered out. Therefore validation is also limited to the geophysically meaningful part of the spectrum (below the second orbit resonance around order 31).

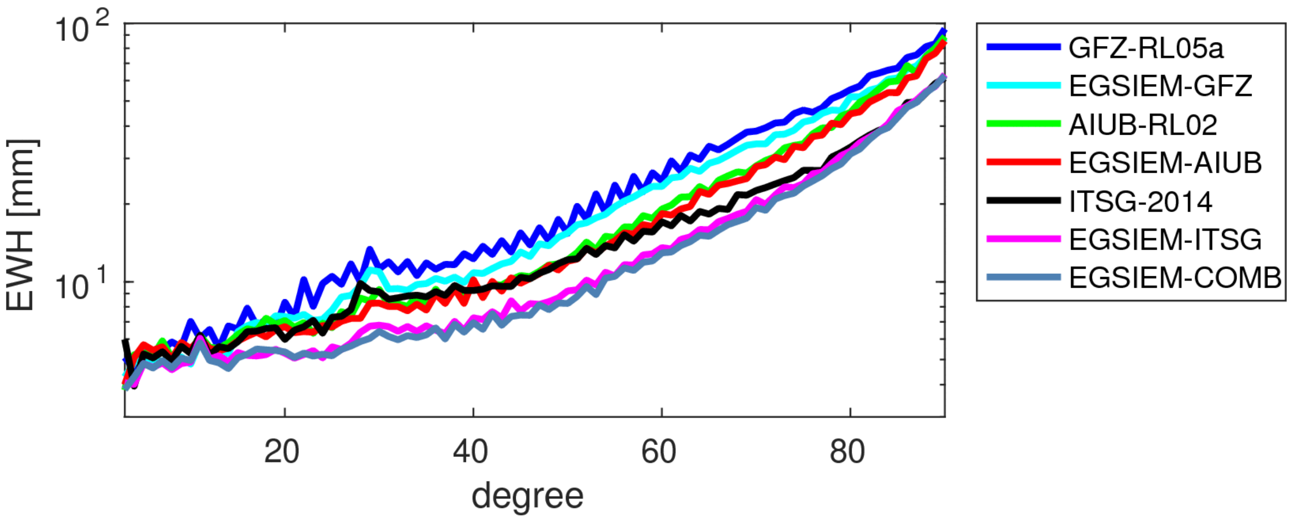

Figure 1: Median degree amplitudes of anomalies in equivalent water height (truncated at order 29).

Compared are EGSIEM-GFZ to GFZ-RL05, EGSIEM-ITSG to ITSG-GRACE2014 and EGSIEM-AIUB to AIUB-RL02. In case of GRGS no fair comparisons are possible because GRGS-RL02 and -RL03 were regularized. ULux did not provide monthly gravity fields. Significant improvements arer visible for EGSIEM-GFZ and EGSIEM-ITSG, minor improvements for EGSIEM-AIUB.

The corresponding comparisons of global grids of anomalies are shown in Figure 2 to Figure 7, this time evaluated up to full order, but smoothed by a 400 km Gauss filter. Instead of showing the median values, the RMS per grid cell is computed for the two test years 2006 and 2007. The anomalies over the continents indicate non-seasonal signal and cannot be used to assess noise levels. But over the oceans only little variability is expected and the visible longitudinal stripes have to be considered as noise (with the exception of some signal near the eastern coast of South America and traces of the Antarctic circumpolar current). Again only small changes are visible in case of AIUB, but major improvemens in terms of noise levels over the oceans for the EGSIEM contributions of GFZ and ITSG.

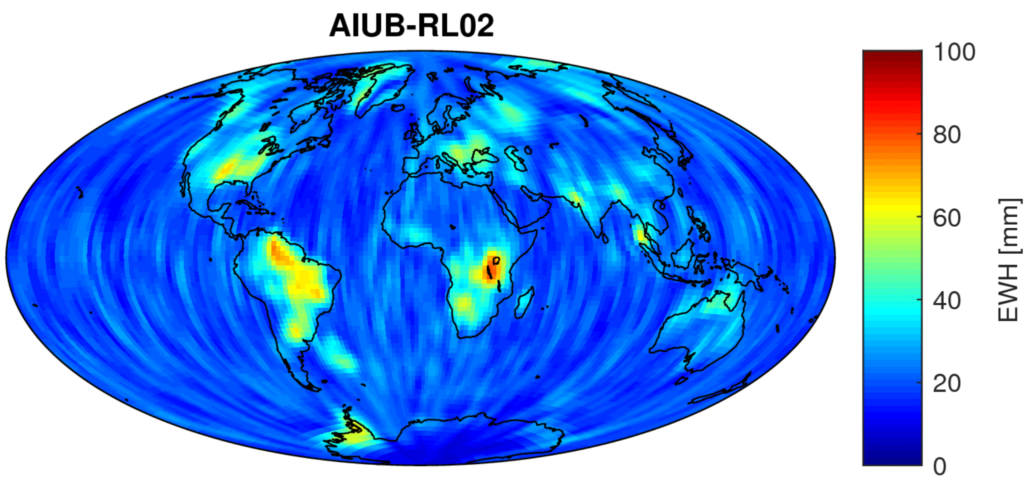

Figure 2: RMS of AIUB-RL02 anomalies, smoothed by a 400 km Gauss filter.

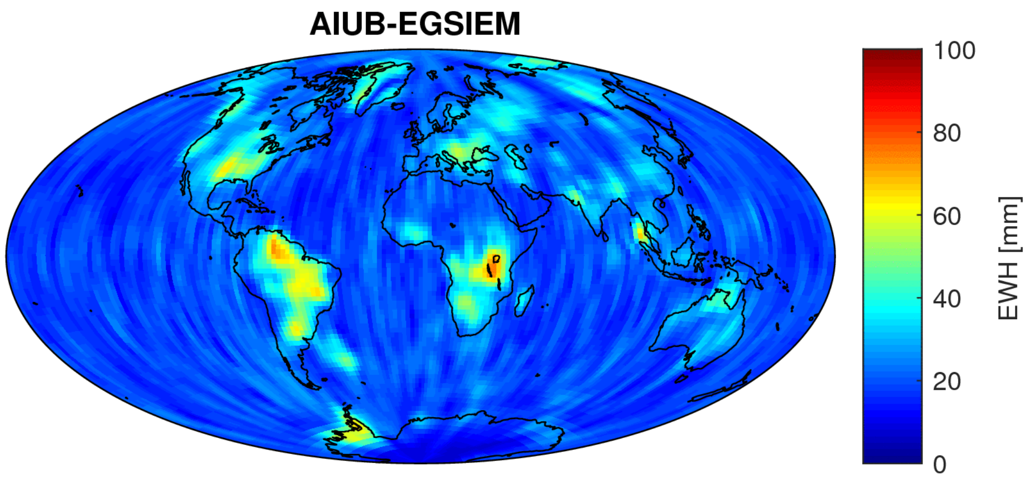

Figure 3: RMS of EGSIEM-AIUB anomalies, smoothed by a 400 km Gauss filter.

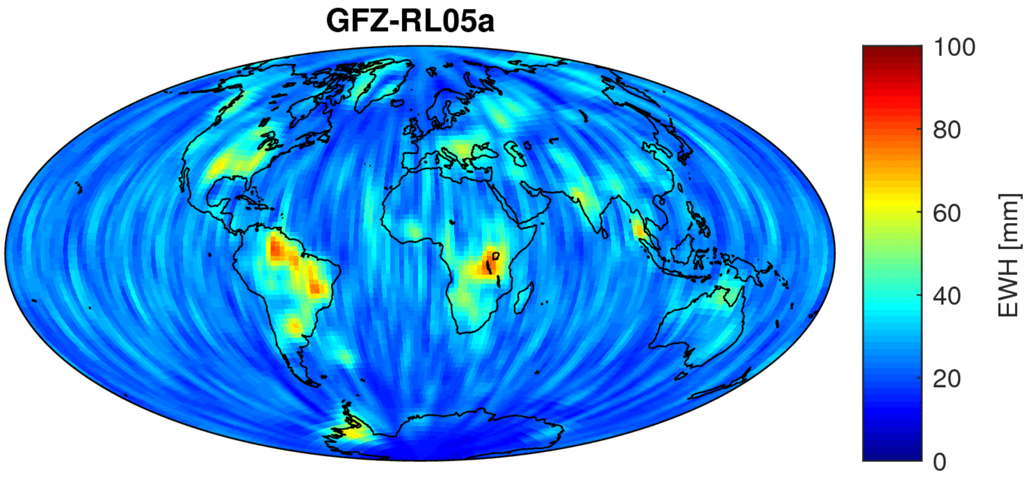

Figure 4: RMS of GFZ-RL05a anomalies, smoothed by a 400 km Gauss filter.

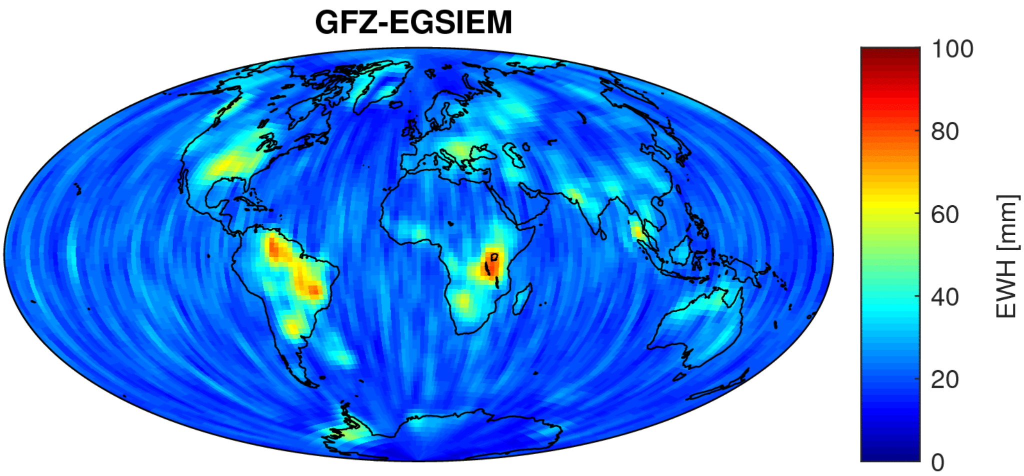

Figure 5: RMS of EGSIEM-GFZ anomalies, smoothed by a 400 km Gauss filter.

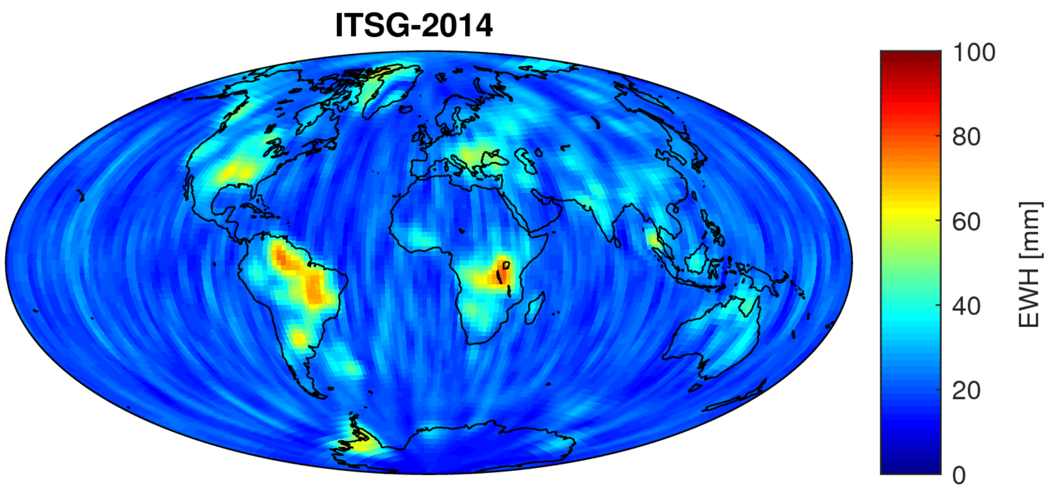

Figure 6: RMS of ITSG-GRACE2014 anomalies, smoothed by a 400 km Gauss filter.

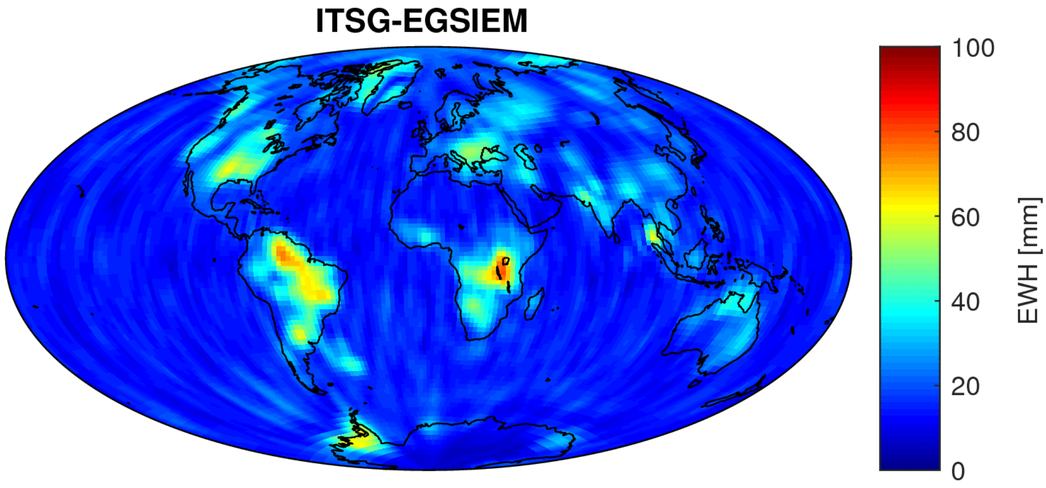

Figure 7: RMS of EGSIEM-ITSG anomalies, smoothed by a 400 km Gauss filter.

Finally the noise over the oceans is evaluated per month. To this end the monthly RMS of the anomalies over the oceans, weighted by the cosine of the grid cells' latitude, is computed. To avoid leakage from the continents a margin of three grid cells, i.e., six degrees, along the coastlines is ignored in the RMS computation. Again the significant improvement, mainly of EGSIEM-GFZ and EGSIEM-ITSG, is clearly visible (Figure 8).

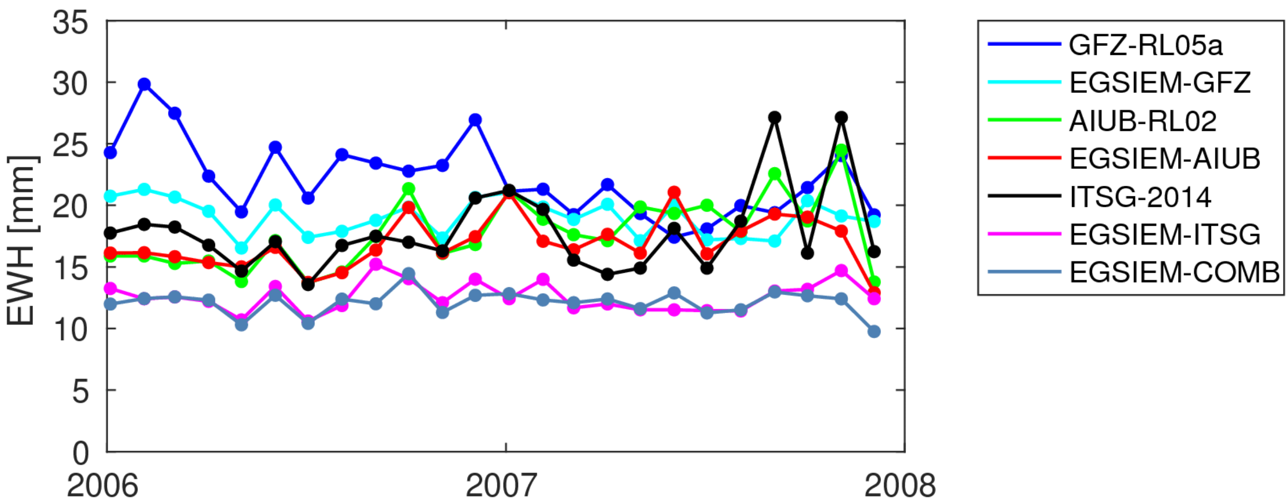

Figure 8: Monthly RMS of anomalies over the oceans, smoothed by a 400 km Gauss filter and weighted by the cosine of the latitude.

4. Combination

After quality control and screening of the individual AC's monthly contributions relative monthly weights were determined by variance component estimation (VCE) on solution level. The process was complicated by the fact that GRGS only provided normal equations / gravity fields up to spherical harmonic degree 80, while AIUB, GFZ and ITSG followd the EGSIEM specifications and delivered up to degree and order 90. Consequently first weights were derived for all four contributions, truncated at degree 80. These weights were used for combination on solution level up to degree 80 and later also for combination on NEQ level (for the complete NEQs, independent of the individual maximum degree). To also obtain combinations on solution level up to full degree 90, in a second step weights were derived for the remaining three contributions, based on all coefficients up to degree 90. All coefficients from degree 81 to 90 were combined on solution level based on the reduced set of contributions and the corresponding relative weights.

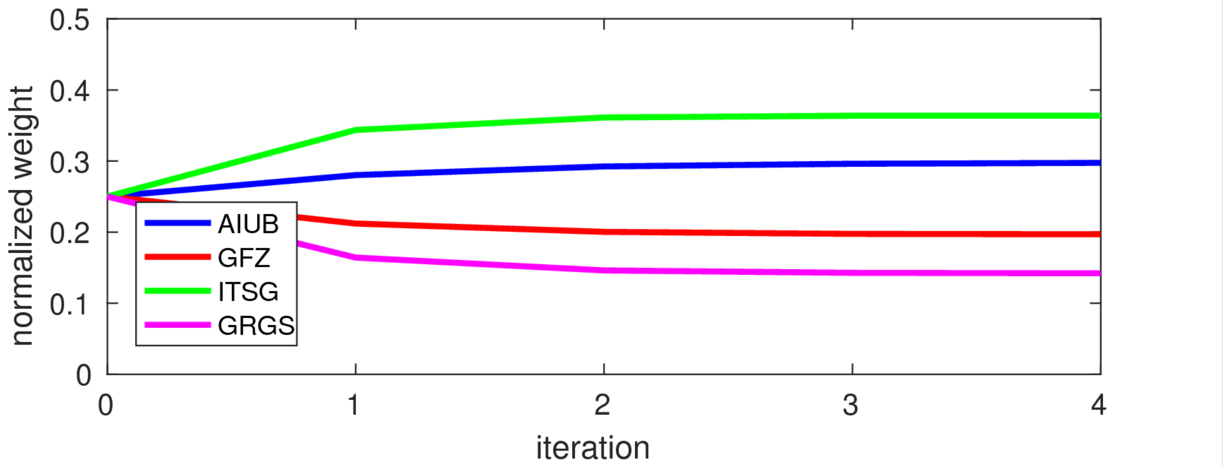

Figure 9: Iterative determination of relative weights by VCE for example month 01/2006.

The iterative determination of the weights by VCE is illustrated in Figure 9 for one example month (01/2006). In most cases the weights converged after 2-3 iterations. Figure 10 shows the corresponding development of the noise level over the oceans, assessed by the standard deviation of all ocean grid cells, weighted by the cosine of the latitude (this in fact is equivalent to the weighted RMS introduced in Section 3).

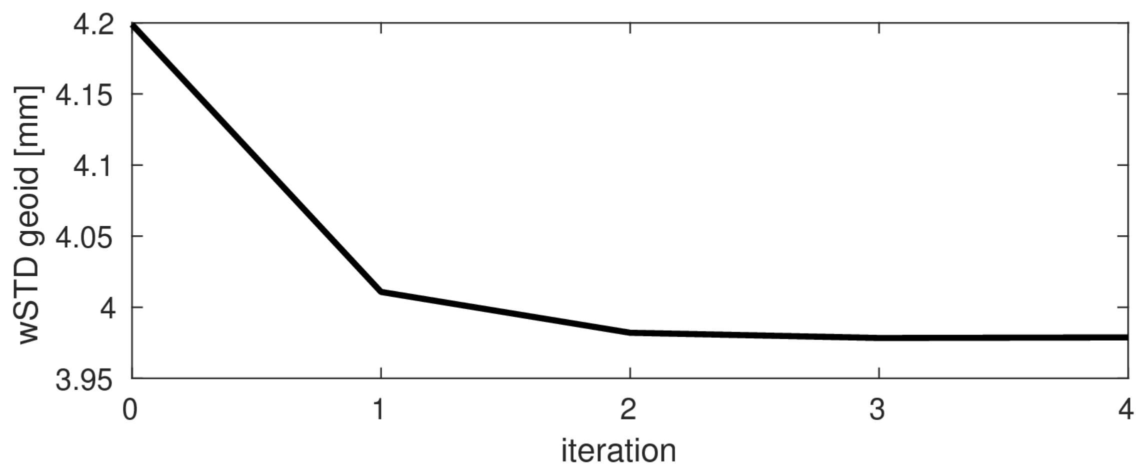

Figure 10: Noise level of different iterations of combined monthly gravity field 01/2006, assessed by STD of anomalies over oceans (weightd by the cosine of the latitude).

The relative weights that represent the noise levels of the individual solutions are the main result of the combination on solution level. The NEQs are combined applying these relative weights (Table 1).

Table 1: Normalized weights (the 10/2006 GRGS contribution was screened out prior to combination).

	AIUB	GFZ	GRGS	ITSG
01/2006	0.2981	0.1970	0.1418	0.3631
02/2006	0.3730	0.2079	0.1512	0.2679
03/2006	0.3796	0.2141	0.1391	0.2672
04/2006	0.3761	0.2160	0.1245	0.2833
05/2006	0.2624	0.2577	0.1665	0.3133
06/2006	0.3108	0.2567	0.1343	0.2981
07/2006	0.3491	0.2232	0.1328	0.2949
08/2006	0.3269	0.1610	0.1052	0.4069
09/2006	0.3182	0.2762	0.1430	0.2626
10/2006	0.3193	0.2917	0.0000	0.3890
11/2006	0.2565	0.2902	0.1168	0.3366
12/2006	0.2276	0.2557	0.1797	0.3370
01/2007	0.2588	0.1688	0.1215	0.4509
02/2007	0.2975	0.2239	0.1112	0.3674
03/2007	0.2902	0.2174	0.1070	0.3854
04/2007	0.3656	0.2062	0.1186	0.3097
05/2007	0.3198	0.1845	0.0967	0.3990
06/2007	0.3664	0.2119	0.1232	0.2986
07/2007	0.3414	0.2108	0.1029	0.3449
08/2007	0.2789	0.1911	0.1221	0.4079
09/2007	0.2458	0.1459	0.1476	0.4607
10/2007	0.3209	0.1636	0.1406	0.3749
11/2007	0.2004	0.2039	0.1517	0.4440
12/2007	0.3506	0.1623	0.1177	0.3694

Prior to combination the individual NEQs have to be scaled to achieve equal impact on pairwise combinations. Otherwise their contribution would depend on the number of observations used (very much dependant on the observation type: GPS phases versus kinematic positions) and the formal errors (dependant on the noise model applied). This scaling is justified because each NEQ is based on the same data set and contains the same signal.

The scale factors are derived empirically by pairwise combination of NEQs. Equal impact is achieved when the RMS of the differences of the individual solutions to the combined solution are equal. The RMS of the differences is computed summing up over all SHC. The GFZ contributions are choosen as reference and their weight is kept fixed at 1. The weights of the AIUB, GRGS or ITSG contributions are stepwise modified from 1 to 10. The RMS of the differences of the individual contributions to the pairwise combinations are plotted in Figure 11 for one example month 01/2006. Equal contribution is achieved on the diagonal black line. The corresponding weights are linearily interpolated between the two nearest hits.

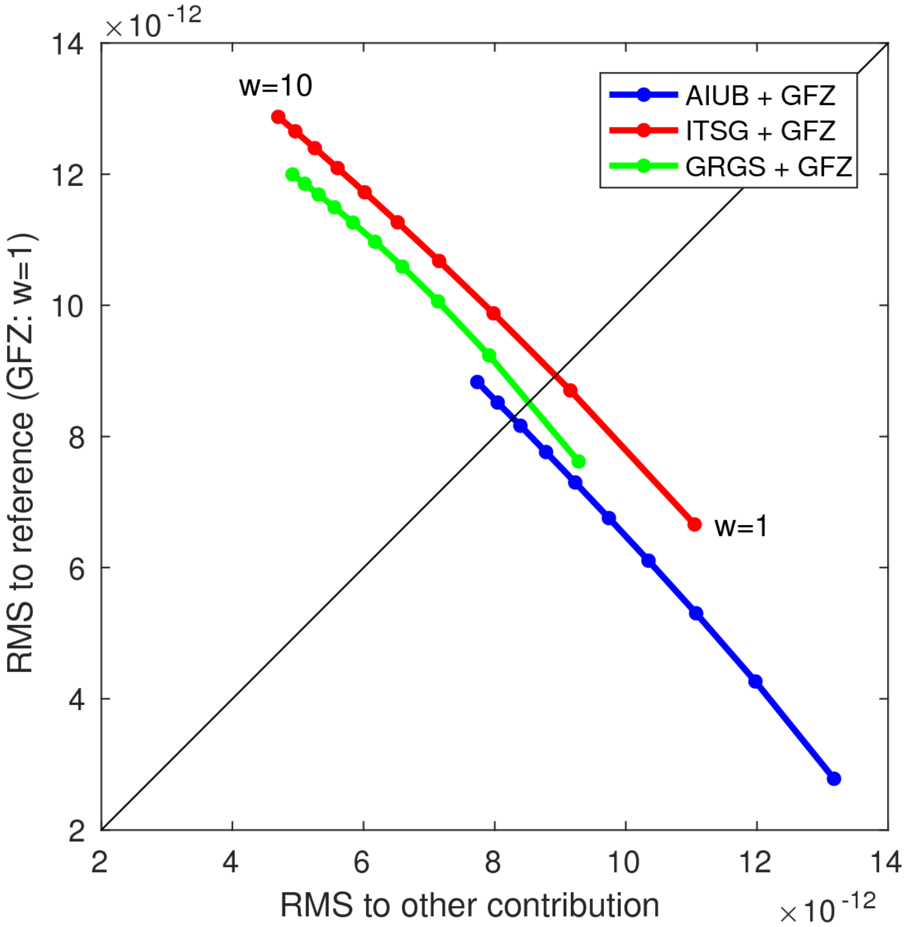

Figure 11: RMS of differences of individual contributions relative to pairwise combinations for example month 01/2006. The weight of the reference contribution from GFZ is kept fixed at 1. The weights of AIUB, ITSG or GRGS take values from 1 to 10. Equal impact is achieved on the black diagonal line.

The scale factors derived for the monthly contributions of the two test years 2006 and 2007 are given in Table 2. Note that these scale factors do not represent quality, but compensate the effect of the different choices of observation types (GFZ and GRGS directly use GPS phases as observations, while AIUB and ITSG first compute kinematic orbits and later use these as pseudo-observations) and the differences in the noise models. The final weights for the combination on NEQ level are derived by multiplication of the weights derived by VCE on solution level by the scale factors derived empirically by pairwise combinations on NEQ level.

Table 2: Scale factors to achieve equal impact (reference is GFZ).

	AIUB	GFZ	GRGS	ITSG
01/2006	8.34	1.00	1.60	2.21
02/2006	6.55	1.00	1.74	2.41
03/2006	7.37	1.00	2.17	2.77
04/2006	7.89	1.00	1.77	2.72

05/2006	8.33	1.00	1.80	2.69
06/2006	9.43	1.00	2.25	5.65
07/2006	7.86	1.00	1.85	3.30
08/2006	7.09	1.00	2.21	2.94
09/2006	7.42	1.00	1.30	4.90
10/2006	10.3	1.00	0.00	4.77
11/2006	7.21	1.00	2.41	2.44
12/2006	6.52	1.00	1.94	1.58
01/2007	6.61	1.00	1.86	2.18
02/2007	7.87	1.00	2.27	2.93
03/2007	6.61	1.00	2.15	2.20
04/2007	7.64	1.00	1.92	2.62
05/2007	7.51	1.00	2.56	2.18
06/2007	6.88	1.00	1.93	2.58
07/2007	8.62	1.00	3.12	2.65
08/2007	8.15	1.00	2.28	2.36
09/2007	6.89	1.00	1.64	2.03
10/2007	6.09	1.00	1.43	2.01
11/2007	9.56	1.00	2.23	2.65
12/2007	6.79	1.00	1.97	2.61

For validation of the monthly combinations anomalies are computed (see Section 3). In Figure 12 degree amplitudes of anomlies for 01/2006 are shown, truncated at order 29 (further months can be found in the appendix, Section 8). Throughout the whole spherical harmonics spectrum both combined solutions (combination on solution level / on NEQ level) are as good as or even better than the best individual contribution (from ITSG), with a possible exception at degree 29 (near the second resonance order 31). At the highest degrees the combination on NEQ level is slightly better than the combination on solution level and it also seems to be more stable against atrifacts in individual contributions (in this case ill-determined sectorial coefficients in the GRGS contribution that enter the degree amplitudes up to degree 29).

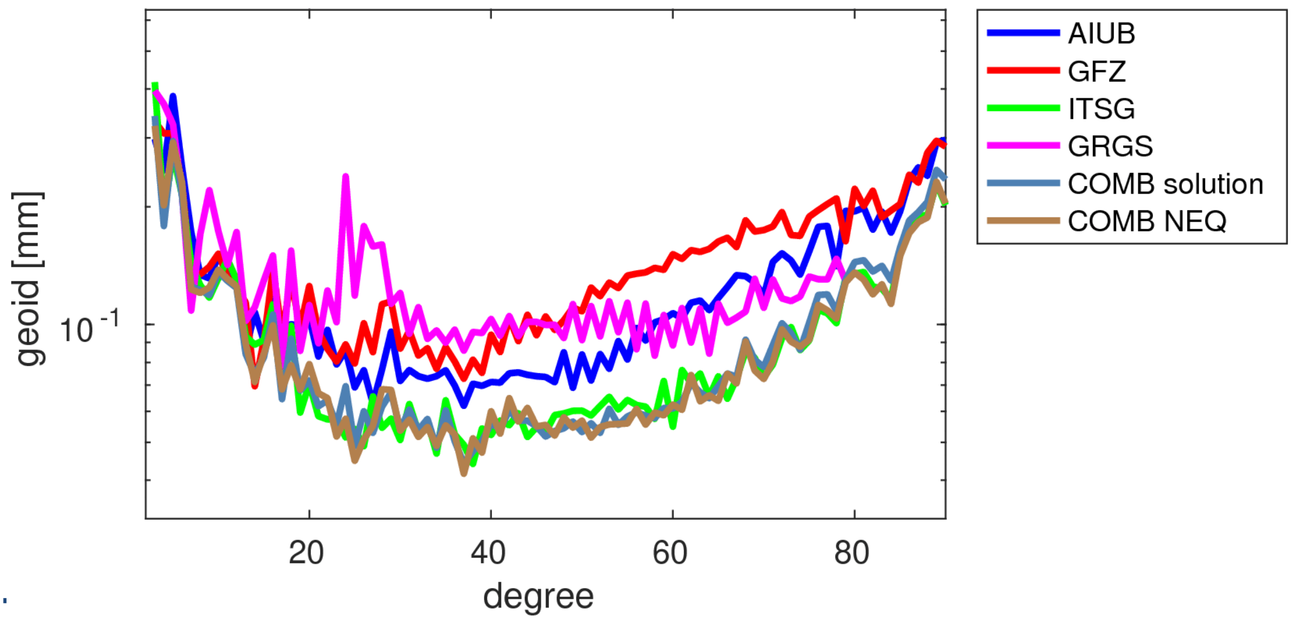

Figure 12: Degree amplitudes of anomalies in geoid height (truncated at order 29).

Repeating the validation in EWH performed in Section 3 including the EGSIEM combined solution on NEQ-level, it outperforms all individual contribution (Figure 13).

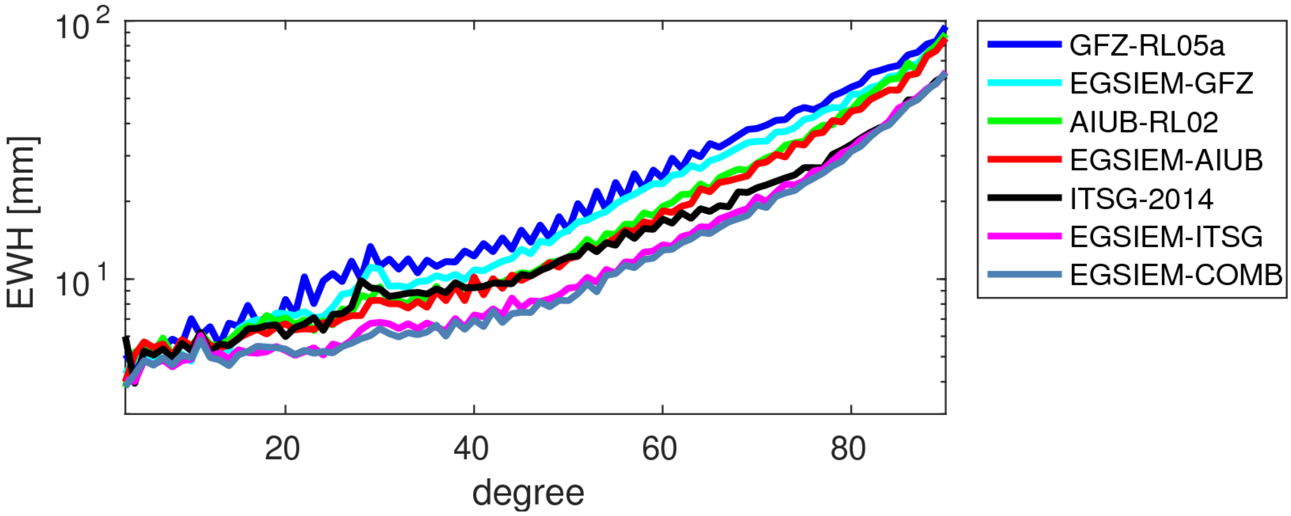

Figure 13: Median degree amplitudes of anomalies in equivalent water height (truncated at order 29).

In Figure 14 the global grid of RMS of anomalies per grid cell (smoothed by a 400 km Gauss filter) is computed for the combination on NEQ-level. The comparison with Figure 2 to Figure 7 (in Section 3) again reveals the decrease in noise over the oceans compared to the individual solutions.

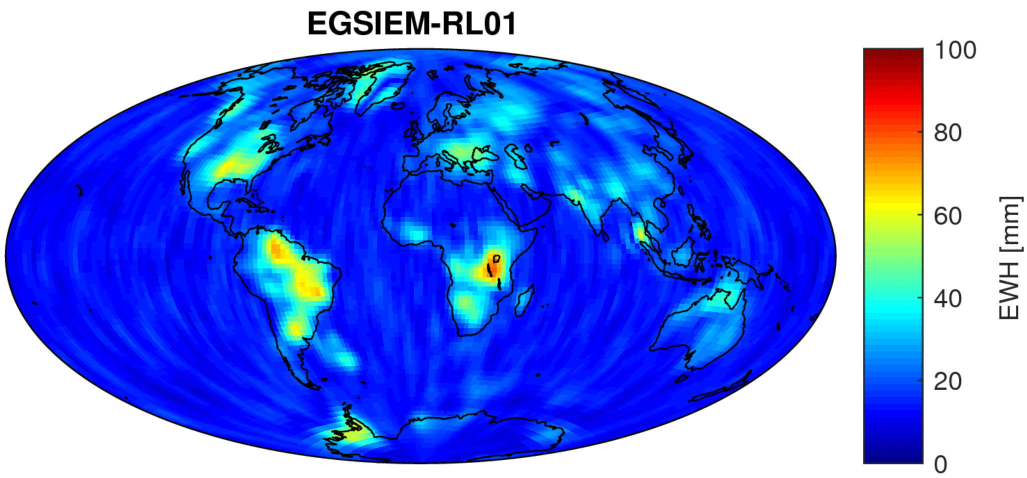

Figure 14: RMS of EGSIEM NEQ-combination anomalies, smoothed by a 400 km Gauss filter.

Finally, Figure 15 shows the monthly evaluation of the RMS over the oceans including the combinations on NEQ-level. The combined monthly gravity fields perform as good or better than the best individual contributions for most months, except for June 2007. This exception is probably caused by the slightly reduced quality of the AIUB and GFZ contributions in this month. In this context it also has to be noted that the relative weights used for the combination are derived based on pairwise comparisons of the individual contributions to their monthly mean. The weights not necessarily represent the noise levels indicated by the anomalies and in consequence the anomalies of the combined gravity fields are not necessarily minimized.

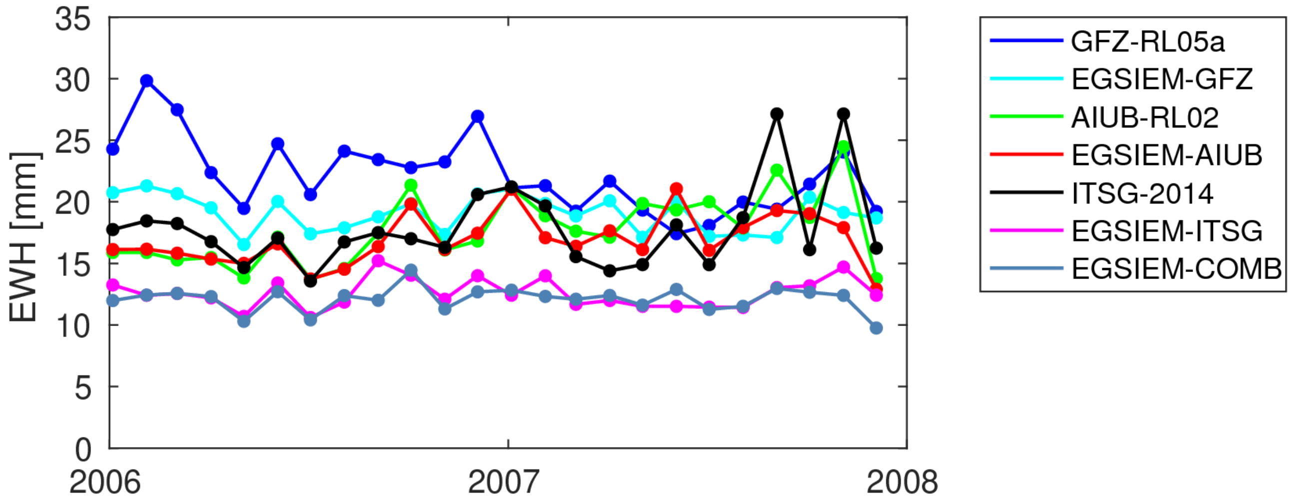

Figure 15: Monthly RMS of anomalies over the oceans, smoothed by a 400 km Gauss filter and weighted by the cosine of the latitude.

For distribution of Level-2 SHC and for derivation of Level-3 grids the EGSIEM combinations on NEQ-level were choosen.

5. Generation of Level-3 products

To make the EGSIEM combined monthly gravity fields attractive for a wide range of users the original Level-2 spherical harmonic coefficients (SHC) are transformed to Level-3 grids. Therefore a number of corrections are applied, depending on pre-defined fields of applications (Table 3), and the gridded products are smoothed specificly for the different applications.

Table 3: Definition of L3-products.

L3-product	Constituents
GRACE non-tidal	GRACE + monthly means of atmosphere and ocean de-aliasing
hydrology	GRACE non-tidal – A – O – GIA
oceanography	GRACE non-tidal + OBP – A – O – GIA – H

Table 4: Definition of constituents.

Constituent	Abbreviation	Model
Atmosphere	A	AOD1B atm
Ocean	O	AOD1B ocn
Ocean Bottom Pressure	OBP	AOD1B oba
Global Isostatic Adjustment	GIA	Geruo A
Hydrosphere	H	WGHM

As a first step the full (non-tidal) signal content is restored. This is necessary because the individual ACs apply de-aliasing models to reduce the impact of atmosphere and ocean mass variations with periods shorter than one month. Further on degree 1 SHC are added, derived by satellite laser ranging (SLR) to 9 satellites (Sosnica et al, 2015). The C_{20} SHC that is weakly determined in the majority of the individual AC's contributions due to the dependency on the accelerometer calibration (Klinger et al, 2016) is not replaced, because in the two EGSIEM test years 2006 and 2007 the combined C_{20} fits very well the SLR derivd values.

To restore full (non-tidal) signal, monthly means of the de-aliasing products are computed specificly for the individual ACs. The monthly mean is defined as the mean of the specific dealiasing product used by the AC, covering the period from the first to the last day used by the AC (due to processing issues the processing tables of the individual ACs may differ). Data gaps within a month are ignored. This strategy is motivated by the assumption that users will also not adapt their data base of hydrological or oceanographic observations to perfectly fit the availability of GRACE data within a month. For the two test years the periods of the monthly gravity fields coincide with the calendar months (in later years of the GRACE mission extended data gaps occure that enforce a definition of the GRACE monthly fields slightly different from the calendar months). The individual ACs monthly means of de-aliasing models are combined applying the same weights as derived for the combination on solution level (also applied for the combination on NEQ level).

While AIUB, GFZ and ITSG are using the official GRACE SDS AOD1B products for de-aliasing, GRGS is using MOG2D. The differences in the monthly means, however, are small, as shown by Figure 16 for the atmosphere component and example month 01/2006.

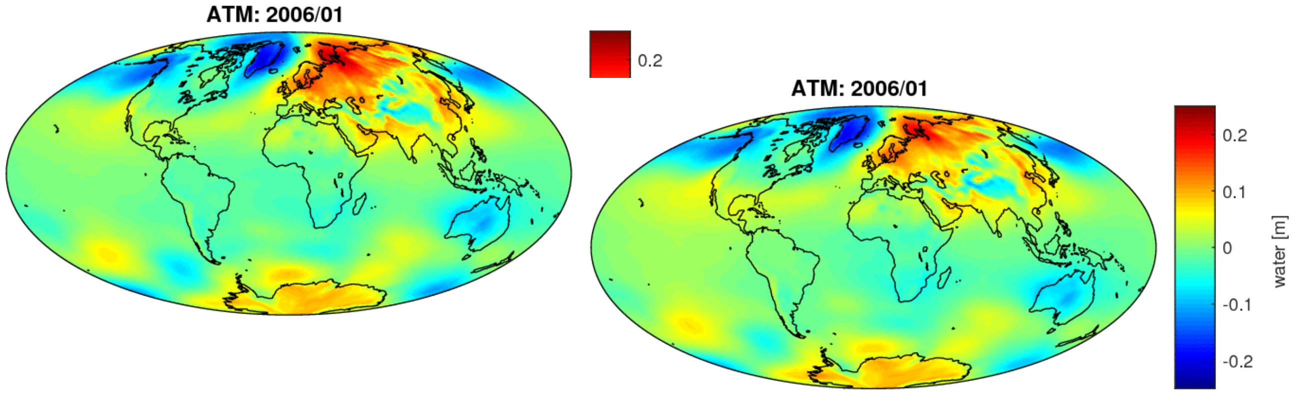

Figure 16: Monthly mean of AOD1B (left) and MOG2D (right) atmosphere de-aliasing 01/2006.

As can be expected the combined monthly mean (Figure 17) of the atmosphere de-aliasing products also is very close to the individual monthly means.

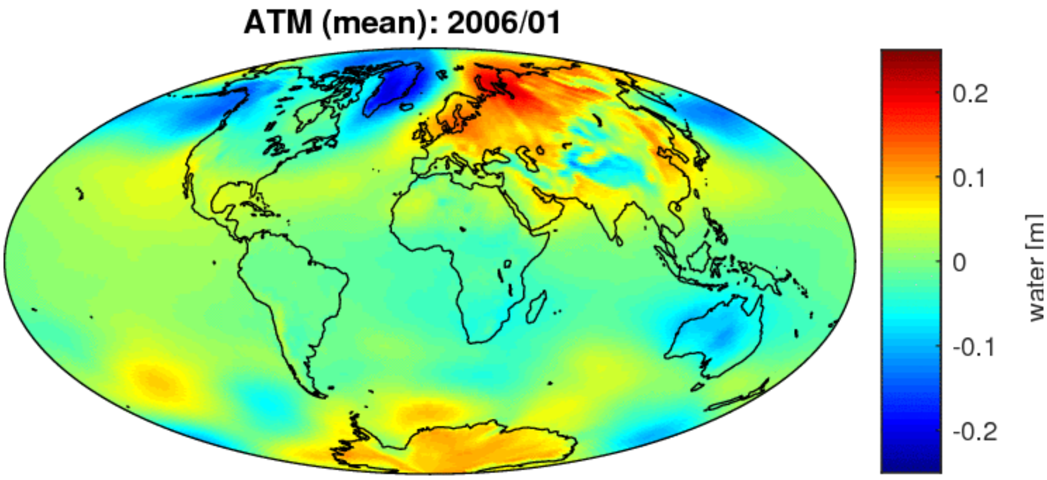

Figure 17: Weighted combination of monthly means of atmosphere de-aliasing 01/2006.

The ocean components of the two different de-aliasing products are shown in Figure 18 for the same example month and the corresponding combined product in Figure 19.

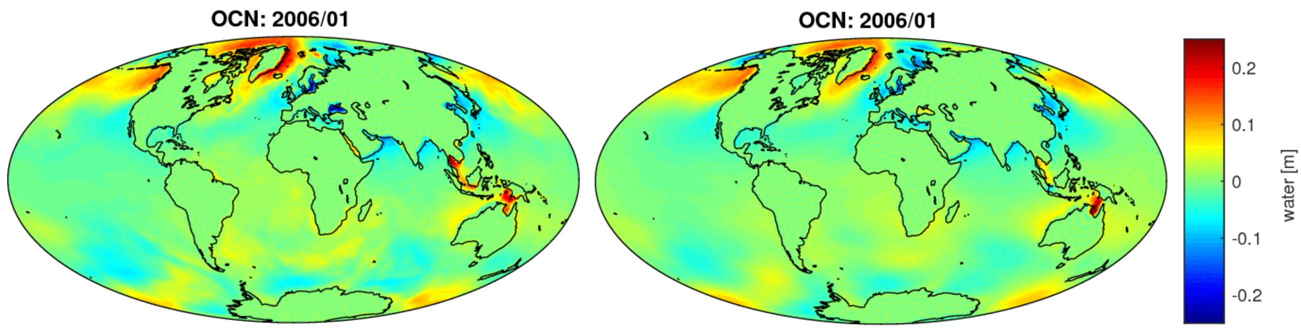

Figure 18: Monthly mean of AOD1B (left) and MOG2D (right) ocean de-aliasing 01/2006.

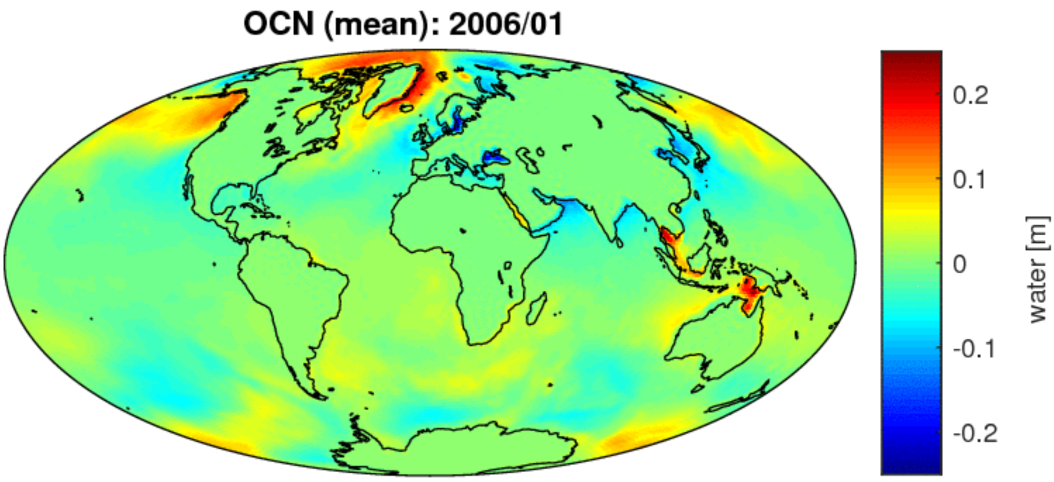

Figure 19: Weighted combination of monthly means of ocean de-aliasing 01/2006.

From the full signal (non-tidal) monthly gravity fields, specific products for different applications are produced by subtraction / addition of models for atmosphere, ocean, or hydrosphere mass variations, as well as corrections due to global isostatic adjustment (GIA) and to transform to ocean bottom pressure in case of oceanographic applications (Table 4). Finally the different products are filtered in the spectral domain and transformed to grids.

Time varying filters for L3 products

For the filtering of the potential coefficients, a time varying filter based on the DDK approach by Kusche et al. (2009) was devised. Instead of using a synthetic error model for GRACE, formal error estimates are used to take into account variations in measurement accuracy and orbit geometry. These error estimates are based on the full error covariance provided by TUG in the ITSG-Grace2016 release (Mayer-Gürr et al. 2016).

To introduce as little prior information in the filtering process as possible, an isotropic signal covariance was chosen. The underlying Kaula-type function was determined by fitting scale and power parameters to geophysical models representing the ocean (AOD1B oba) and hydrosphere (WGHM) subsystems. In accordance with the findings of Chambers and Bonin (2012) when evaluating the CSR RL05 release, the lower noise level of the EGSIEM solutions allowed the SHC below degree 15 to remain unfiltered.

Visualization and distribution of L3 products

The L2 spherical harmonic coefficients as well as the L3 grids for oceanographic and hydrological applications and all the individual constituents can be visualized using the EGSIEM plotter (http://plot.egsiem.eu). The plotter allows to evaluate the time series over certain regions or to compare general overview graphics of the different products in spherical harmonic or spatial domain (Figure 20 and Figure 21). The different filter characteristics depending on the field of application are obvious comparing the spherical harmonic spectra or the signal content in the spatial domain in both figures. The L2 SHC and L3 filtered grids for oceanographic or hydrological applications can be downloaded via link on the EGSIEM webpage (http://www.egsiem.eu) from ftp://ftp.unibe.ch/aiub/EGSIEM. They are available for the two EGSIEM test years for operational combination 2006 and 2007.

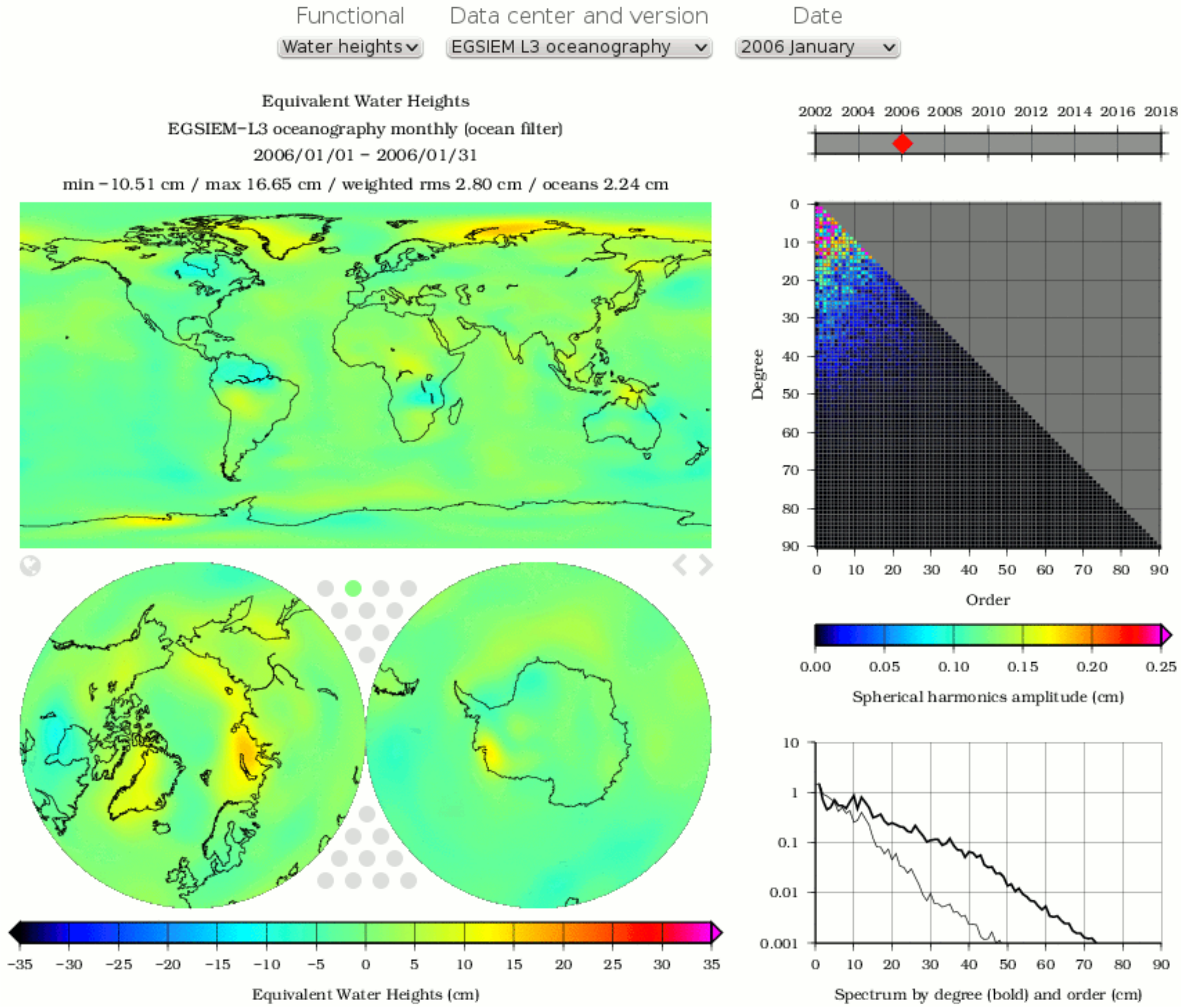

Figure 20: Filtered and gridded combined solution 01/2006 for oceanographic applications (left) and the corresponding spherical harmonics spectrum (right).

Note on the GIA model

The Associated Member Lantmäteriet (LM; the Swedish mapping, cadastral and land registration authority) in Sweden develops a series of Glacial Isostatic Adjustment (GIA) models to be provided to the EGSIEM consortium for helping to separate the hydrological trend. For the ice history model part of the GIA model, LM combines regional ice history models, kindly provided by their developers, to a global one. The first GIA model that is now ready for use for GIA correction in the EGSIEM plotter is based on an ice model called LM17.3 and the laterally homogeneous VM5a earth model (Argus et al. 2014, Peltier et al. 2015). It is planned to provide an update within the next months with a slightly improved ice model and a laterally heterogeneous (3D) earth model.

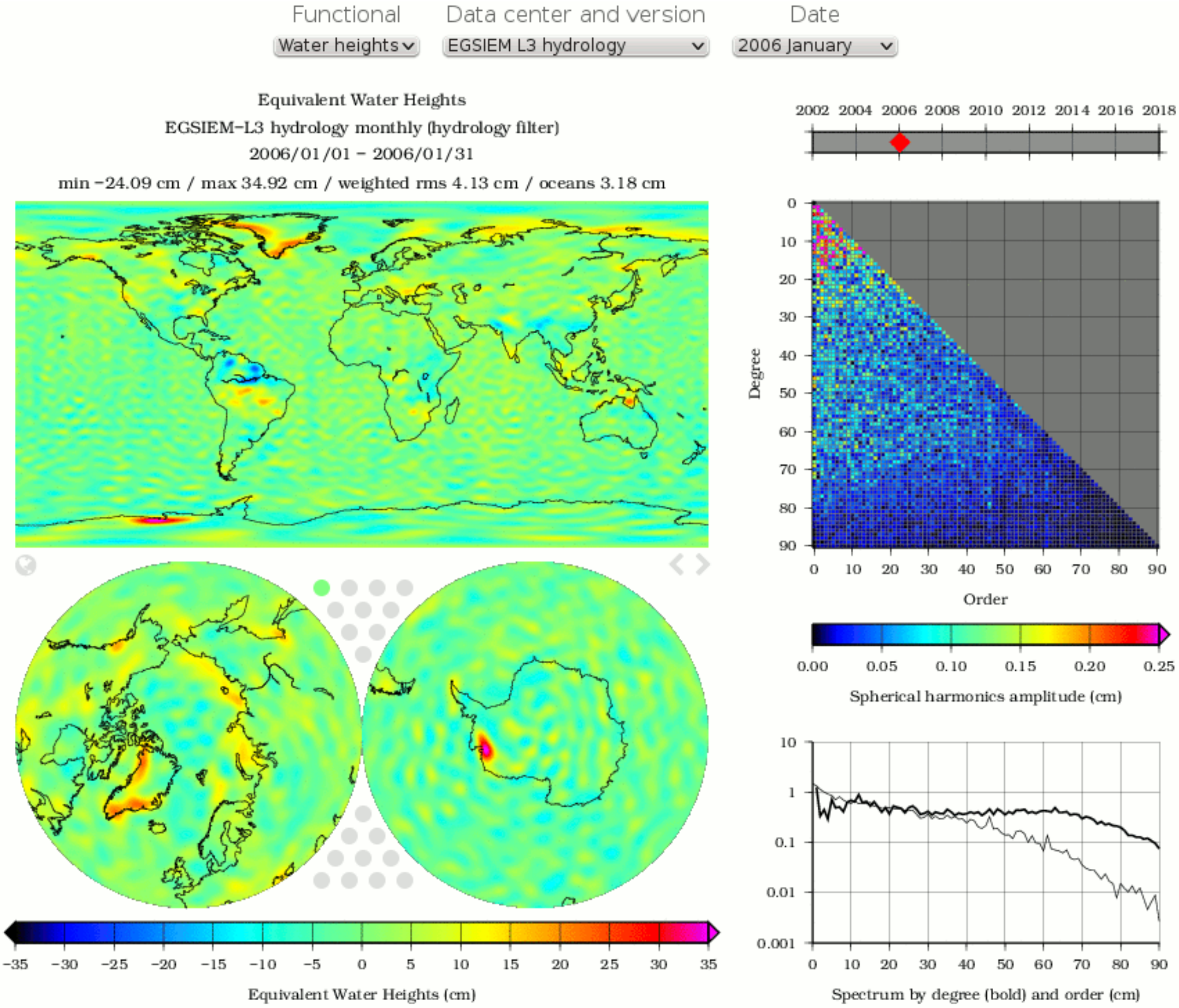

Figure 21: Filtered and gridded combined solution 01/2006 for hydrologic applications (left) and the corresponding spherical harmonics spectrum (right).

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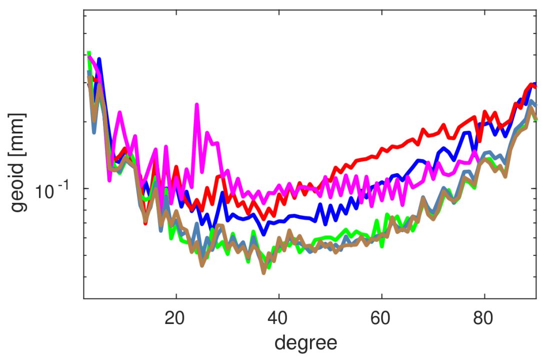
7.Glossary

AC	Analysis Center
AIUB	Astronomical Institute of the University of Bern
CSR	Center for Space Research, Austin, Texas
GFZ	Helmholtz Centre Potsdam, German Research Centre for Geosciences
GIA	Global Isostatic Adjustment
GRACE	Gravity Recovery and Climate Experiment
GRGS	Groupe de Recherche de Géodésie Spatiale, Toulouse, France
ICGEM	International Center for Global Earth Models
ITSG	Institute of Theoretical and Satellite Geodesy (now IfG), University of Graz
NEQ	Normal EQuation
OBP	Ocean Bottom Pressure
RMS	Root Mean Square
SDS	Science Data System
SHC	Spherical Harmonic Coefficients
SLR	Satellite Laser Ranging
STD	Standard Deviation
TUG	Technical University of Graz
VCE	Variance Component Estimation

8. Annexes

The following table comprises degree amplitudes of anomalies (up to order 29) of all monthly combinations processed in the frame of the test run for operational service, i.e., of the two EGSIEM test years 2006 and 2007. The 10/2006 contribution of GRGS did not pass the screening due to increased noise level and was not included in the combination.

01/2006



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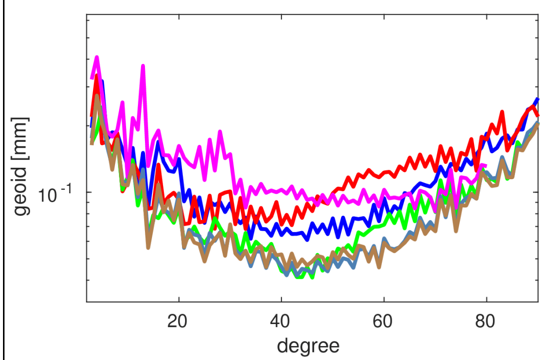

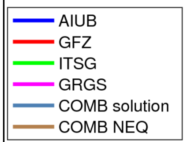

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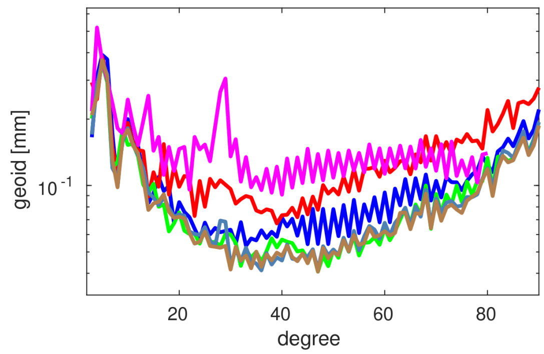

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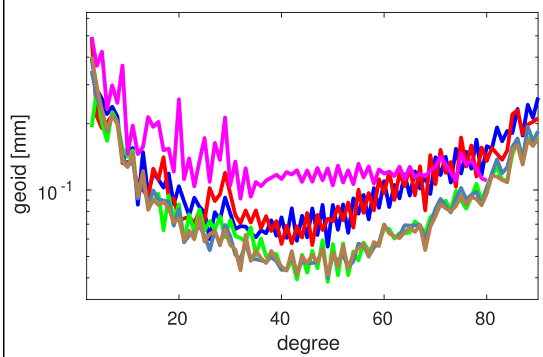

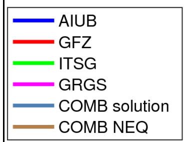

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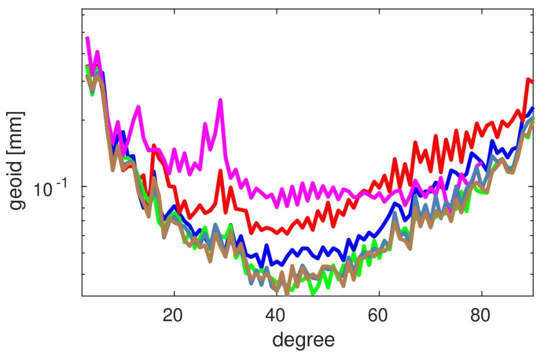

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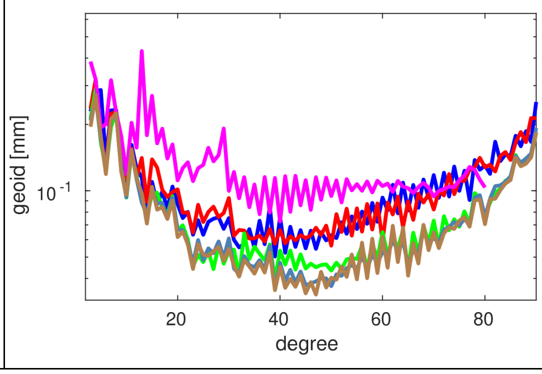
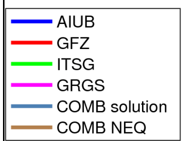
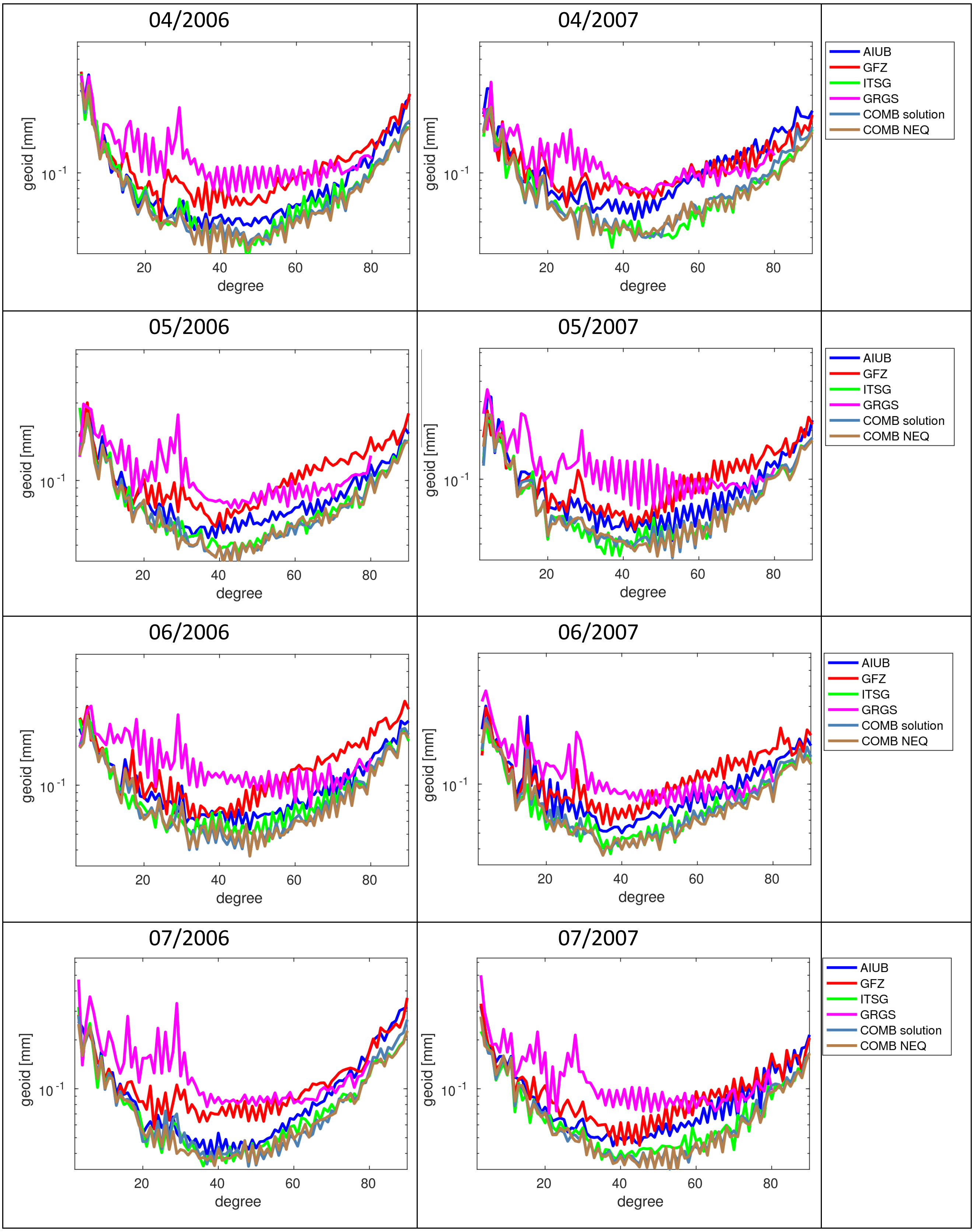
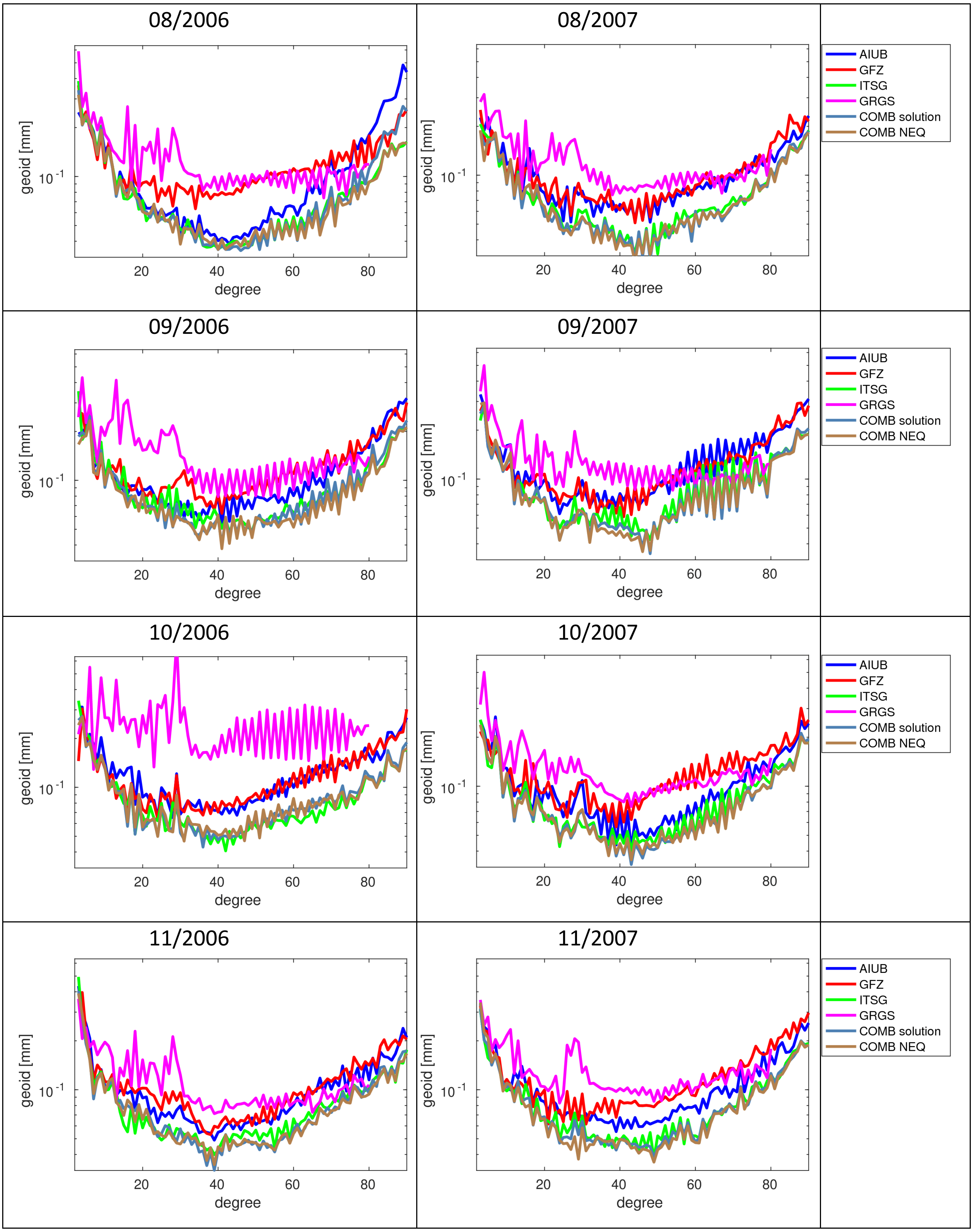





04/2006
04/2007
05/2006
05/2007
06/2006
06/2007
07/2006
07/2007
geoid [mm]
10 -1
degree
20
40
60
80
AIUB
GFZ
ITSG
GRGS
COMB solution
COMB NEQ


08/2006
08/2007
09/2006
09/2007
10/2006
10/2007
11/2006
11/2007
geoid [mm]
10^{-1}
20
40
60
80
degree
AIUB
GFZ
ITSG
GRGS
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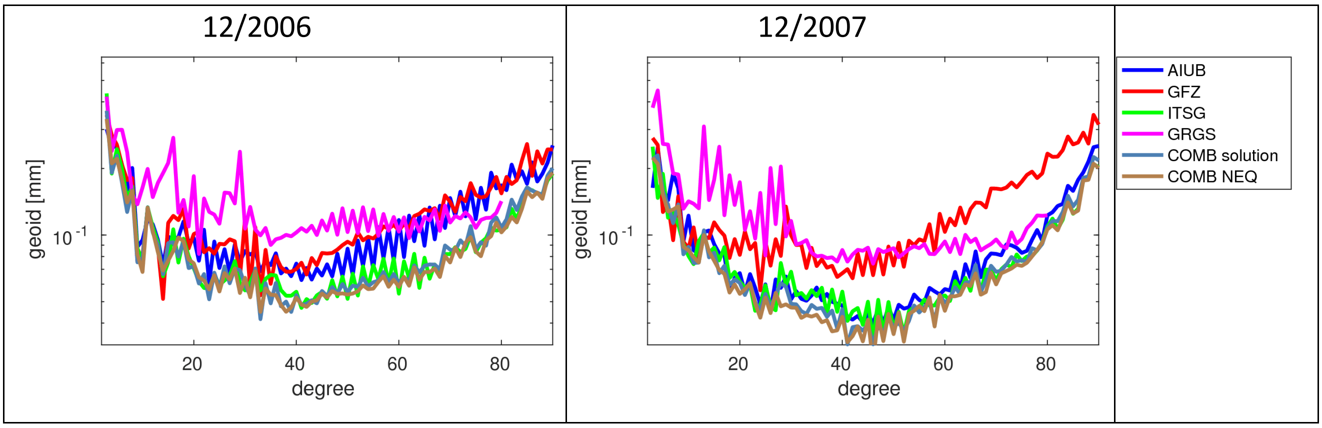
12/2006
12/2007
geoid [mm]
10^{-1}
20
40
60
80
degree
AIUB
GFZ
ITSG
GRGS
COMB solution
COMB NEQ