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Scientific Technical Report STR08/12

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Imprint

Helmholtz Centre Potsdam
**GFZ German Research Centre
for Geosciences**

Telegrafenberg
D-14473 Potsdam

Printed in Potsdam, Germany
November 2008

ISSN 1610-0956

This work is published in the GFZ series
Scientific Technical Report (STR)

A long-term model for non-tidal atmospheric and oceanic mass redistributions and its implications on LAGEOS-derived solutions of Earth's oblateness

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Abstract

The dynamic oblateness of the Earth, in terms of the J_2 or C_{20} coefficient of the Earth´s geo-potential has been derived by analysis of LAGEOS Satellite Laser Ranging (SLR) data. Although recent analyses of GRACE (Gravity Recovery and Climate Experiment) mission data of monthly C_{20} values since 2002 have shown high temporal correlations with LAGEOS results, significant differences still remain. As it is common practice in GRACE data processing to remove a priori the short-term non-tidal atmospheric and oceanic induced variations of the gravity potential via the so-called Atmosphere and Ocean De-aliasing Level-1B (AOD1B) products, their use for LAGEOS data processing would allow a direct comparison of results and a rigorous combination of the solutions. Since the consideration of short-term non-tidal atmospheric and oceanic mass redistributions by means of AOD1B time series reveals a significant impact on LAGEOS data processing results, the AOD1B time series has been consistently prolongated back to the advent of LAGEOS-1 in 1976. An analysis for the period 1993-2006 leads to the major findings that the consideration of atmospheric and oceanic mass redistributions result in a considerably reduced seasonal signal in the LAGEOS C_{20} time series. This in turn reduces the correlation to GRACE significantly by about 30%. This is in opposite to what one would expect, i.e., a better agreement between GRACE and LAGEOS if common standards are applied. Thus, a LAGEOS solution corrected for short-term non-tidal atmosphere and ocean effects is much less sensitive to primarily annual hydrological mass variations than GRACE. In addition, significant semi-annual signals remain. Other indicators such as the unresolved bias between LAGEOS and GRACE in the order of $2 \cdot 10^{-10}$ or LAGEOS orbits and Satellite Laser Ranging (SLR) observation residuals are hardly affected by the AOD1B model.

Keywords Dynamic oblateness, Gravity field, Non-tidal mass variations, Atmosphere and ocean de-aliasing, LAGEOS, GRACE

1. Introduction

The initial force field considered during Precise satellite Orbit Determination (POD) of CHAMP and GRACE includes - besides Earth and third bodies gravity effects or non-gravitational forces observed by on-board accelerometers - temporal gravity variations due to solid Earth, atmosphere and ocean tides by the use of appropriate tidal models (Reigber et al., 2005). Modern missions such as CHAMP, GRACE and GOCE which derive the Earth's static and time-variable gravity field with unprecedented accuracy with monthly or even sub-monthly resolution are sensitive to short-term (weekly or shorter) non-tidal mass variations due to mass transports and mass redistribution phenomena in the atmosphere, the oceans and the continental water storage. The correction of these high-frequency impacts, which can reach up to 2 mm in terms of geoid height at wavelengths of 500 km according to analysis of GRACE real data or simulations performed by Thompson et al. (2004), by appropriate models is commonly called "de-aliasing" in the GRACE community.

Precise global and high spatial and temporal resolution hydrological models are not yet available and are therefore not taken into account during gravity field determination. Non-tidal high-frequency atmospheric and oceanic mass variation models, however, are routinely generated at GFZ Potsdam as so-called GRACE Atmosphere and Ocean De-aliasing Level-1B (AOD1B) products to be added to the background static gravity model during GRACE monthly gravity field determination. Consequently, the outputs of the GRACE mission are spherical harmonic coefficients that signify the sum of all unmodelled mass redistribution in the system Earth during given months. Neglecting small scale or small amplitude effects such as post glacial rebound or ocean mass variability the prime result are therefore monthly maps of the global continental hydrological cycle (e.g., Schmidt et al., 2006). Although, in principle, it is a non-unique inverse problem (Chao, 1995), these maps are generally deduced from the spherical harmonic gravity coefficients in terms of thin layer water height changes for filter lengths down to approximately 400 km applying, e.g., the formulae suggested by Wahr et al. (1998). Besides monitoring of the annual and semi-annual cycle of prominent continental water basins such as Amazon or Congo, GRACE data have also been studied to analyse various geophysical phenomena, such as mass balance of ice sheets in Antarctica and Greenland, the corresponding contribution to sea level change, ocean mass variability and redistribution, ocean tides, sterical effects when combined with satellite altimetry, post glacial rebound in Canada and Fennoscandia, vertical crustal displacements when combined with GPS, or relativistic effects such as dragging of inertial frames.

2. The Standard AOD1B Product

The GRACE AOD1B products are 6-hourly series of spherical harmonic coefficients up to degree and order 100 which are routinely provided to the GRACE Science Data System and the user community with only a few days time delay. These products reflect spatiotemporal mass variations in atmosphere and oceans deduced from operational atmospheric weather data and corresponding ocean dynamics simulated as response to wind stresses, atmospheric pressure as well as heat and freshwater fluxes provided by an ocean model (Flechtner et al., 2006). Due to its huge vertical extension, atmospheric mass anomalies cannot be taken into account by means of a thin layer approximation via surface pressure (SP) data, but have to be deduced from a vertical integration (VI) over pressure levels. This so-called 3D problem has been studied by various authors (e.g., Boy and Chao, 2005 or Velicogna et al., 2001) and can result in weighted root mean square (wRMS) geoid height errors of some tens of a millimeter. The variability is derived by subtraction of a long-term mean of vertical integrated atmospheric mass distributions covering the period 2001-2002 and a corresponding mean of ocean bottom pressure as simulated with an ocean general circulation model. The latest model version is called AOD1B RL04 and is, as all other previous releases, based on 6-hourly 0.5° analysis meteorological fields of the Integrated Forecast System of the European Centre for Medium-range Weather Forecasts (ECMWF) and output from the baroclinic ocean model OMCT (Ocean Model for Circulation and Tides, Thomas et al. 2001) forced with these 6-hourly ECMWF analyses (for details, see Flechtner, 2007a; Dobslaw and Thomas, 2007).

3. C_{20} Variability from LAGEOS and GRACE

Within a re-processing campaign of LAGEOS SLR tracking data inside the GGOS-D project (Global Geodetic Observing System – Deutschland) covering the period 1993 to present GRACE-like processing standards are applied in order to derive a consistent long-term series of Earth rotation parameters, station coordinates and low degree gravity field parameters (König et al., 2007). Although these processing standards are very similar to the latest GRACE RL04 standards (Flechtner, 2007b), a de-aliasing product has not yet been taken into account. The long-term C_{20} time series compares well with variations calculated previously by Cheng and Tapley (2004). While the weekly GFZ solution is naturally characterised by a larger scatter than the monthly time-series provided by Cheng and Tapley, the seasonal behaviour of the curves is quite similar. To allow for quantitative comparisons with monthly GRACE estimates, the weekly solutions are combined to four-weekly, smoother solutions. According to Figure 1, C_{20} results derived from LAGEOS data processing at CSR (Cheng and Ries, 2008) and GFZ (both without applying an AOD1B model) show – besides the good agreement of the seasonal signal driven by meteorological mass redistribution in the atmosphere-hydrosphere-cryosphere system (Cox and Chao, 2002) - an up to now inexplicable bias of about $2 \cdot 10^{-10}$ with respect to those deduced from GFZ GRACE Release 04 data analysis using AOD1B. This is also true for the C_{20} values calculated by the two other GRACE SDS processing centres, JPL and CSR (not shown) and is still matter of discussion within the GRACE project. Otherwise the variability of GRACE and LAGEOS is highly correlated, albeit structures in the order of $1\text{-}2 \cdot 10^{-10}$ still remain.

4. Gravity Variations as seen by CHAMP, GRACE, GOCE and LAGEOS

Figure 2 shows gravity variations in terms of geoid heights as deduced from 6-hourly ECMWF vertical integrated pressure data, 6-hourly ocean bottom pressure fields as simulated with OMCT and monthly continental water height changes resulting from the WaterGap Hydrological Model (WGHM, Döll et al., 2003), and the sensitivity of LAGEOS, CHAMP, GRACE and GOCE to these signals. While GOCE is primarily sensitive to atmospheric mass variations up to approximately degree 15, CHAMP and even more GRACE results are highly influenced by all three kinds of signals. Obviously, there is a clear indication that for the very first degrees also LAGEOS is sensitive to atmospheric and, to a lesser extent, to oceanic mass variations. In contrast to GRACE, a correlation with hydrological mass variations is not obvious. However, it can be concluded that for a consistent comparison of low degree coefficients the AOD1B model has to be accounted for during LAGEOS processing as well.

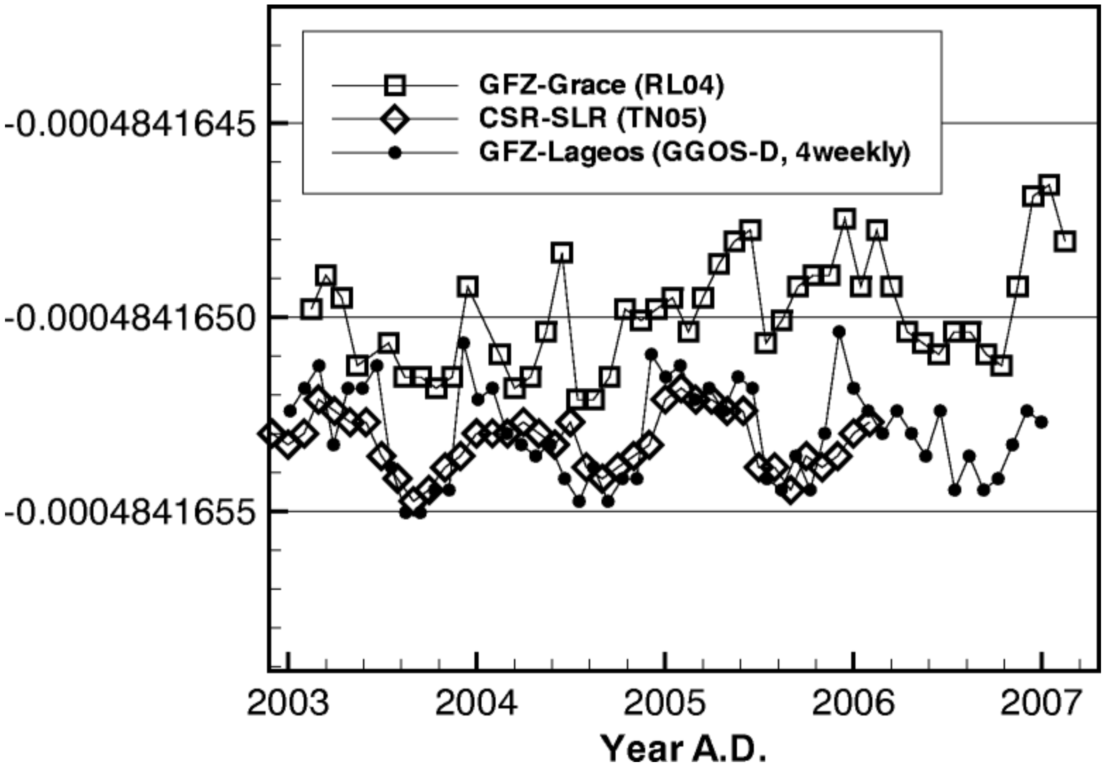

Fig. 1 Monthly C_{20} values derived from GFZ GRACE Release 04 data analysis, monthly and 4-weekly C_{20} values from CSR SLR and GFZ LAGEOS data analysis (both without applying AOD1B), respectively.

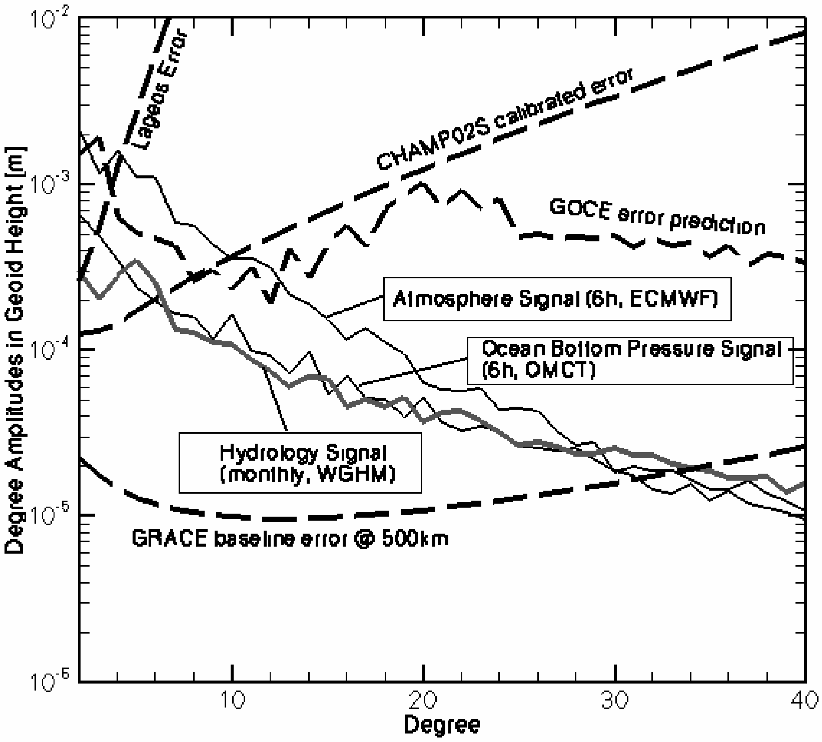

Fig. 2 Gravity variations in terms of geoid height estimated from ECMWF 6-hourly vertical integrated pressure, 6-hourly OMCT ocean bottom pressure and monthly WGHM continental water height

changes (solid lines) and the sensitivity of LAGEOS, CHAMP, GRACE and GOCE to this signals (long dashed lines).

Consequently, we first generated a consistent AOD1B model back to the advent of LAGEOS-1 in 1976 to get a long-term model to be used for correction of LAGEOS but also for other geodetic satellite missions important for the long-term evaluation of the low-degree gravity field such as STARLETTE, AJISAI or others. Secondly, we investigated for the period 1993-2006 the resulting change in C_{20} amplitude and phase and the correlation with seasonal hydrological mass variations as provided by WGHM and GRACE as well as the influence of AOD1B on LAGEOS SLR derived orbits and fits. We will not investigate the impact of AOD1B on the station coordinates, as we consider here solely the dynamic effect. The geometric or loading effect would need dedicated modelling as done, e.g., by Bos and Scherneck (2008) for ocean tide loading.

5. Influence of non-tidal mass variations in atmosphere and oceans on LAGEOS-derived low degree harmonics for the GRACE mission period

To get a first impression of the influence of AOD1B on LAGEOS data processing the period 2003 till 2006, where AOD1B models are already available, has been investigated. Exemplarily, low-degree spherical harmonics of the Earth´s gravity field of the GFZ weekly LAGEOS solutions using the AOD1B RL04 models have been contrasted to corresponding “standard” LAGEOS solutions which have been derived without correcting for short-term non-tidal mass variations. According to Figure 6 and Table 2, the annual plus semi-annual differences for the C_{20} coefficient time series are highly correlated (0.80), but the annual amplitude decreases by more than a factor of 3 and the pronounced seasonal behaviour of the “standard” C_{20} solutions (Figure 1) is largely reduced when correcting for short-term atmospheric and oceanic mass variations. The semi-annual amplitudes remain roughly the same and the annual and semi-annual phases change slightly by about 3 weeks. Therefore, it can be concluded that as for CHAMP, GRACE and GOCE AOD1B products have always to be taken into account when processing LAGEOS data and thus have to be made available back to 1976, the advent of LAGEOS-1.

6. Extension of the AOD1B product time series back to 1976

So far, AOD1B RL04 products are available for CHAMP and GRACE processing for the period January 2001 until present. A consistent prolongation back to 1976, when LAGEOS-1 was launched, cannot be performed directly because the necessary OMCT model output for the period covered by LAGEOS data is based on two principally different atmospheric forcing models. While until 2001 atmospheric forcing fields provided by ECMWF’s reanalysis project ERA-40 were applied, oceanic mass variations for recent years since 2001 were simulated with ECMWF's operational analysis data. This change in forcing was done because of the superiority of ERA-40 compared to operational analysis data at least up to 1999 (Uppala et al., 1999), the increase of the 4D-Var operational analysis assimilation window from 6 to 12 hours on September 12, 2000, and the increase of the operational analysis data spatial resolution from T320 (corresponding to 0.56°) to T520 (0.35°) on November 21, 2000.

Therefore, to generate consistent atmospheric and oceanic non-tidal mass anomalies for processing of LAGEOS data, two sensitivity tests have been performed by generating two additional AOD1B test series for 2004. Firstly, the vertical structure of the atmospheric masses has been neglected by global substitution of VI by surface pressure (SP) data. Secondly, ocean bottom pressure variations over the oceans have been set to zero what corresponds to the simplified assumption that the sea surface reacts exactly like an inverse barometer (IB) and density variations within the local water column (called non-IB or NIB) are negligible. According to the C_{20} variations shown in Figure 3 (left), the difference between VI and SP is insignificant for the processing of LAGEOS data, while the omission of oceanic mass variations results again in seasonal signals similar to the values obtained without AOD1B (Figure 6), but here with slightly smaller amplitude. Thus, for LAGEOS data analysis back to 1976 an AOD1B product based on OMCT mass anomalies and atmospheric surface pressure is sufficient.

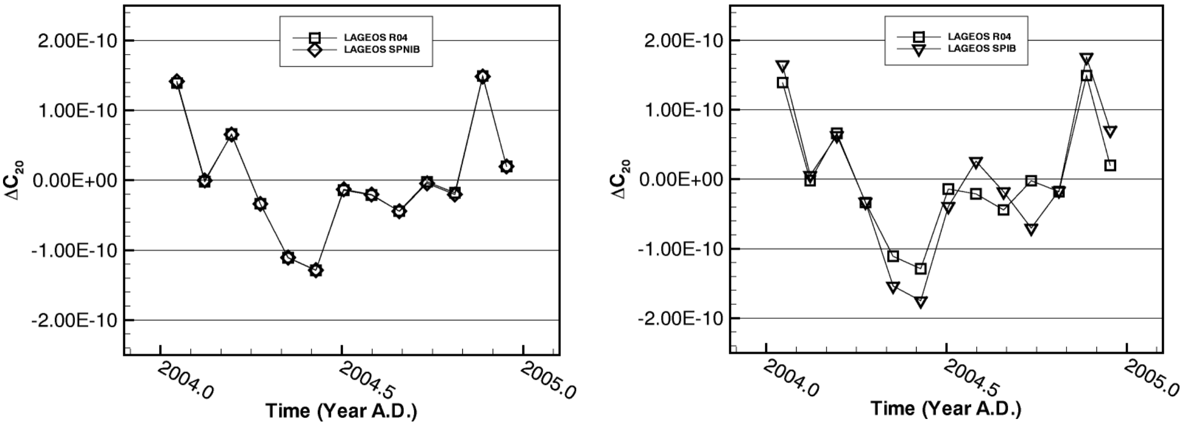

Fig. 3 C_{20} variability for 2004 derived from LAGEOS using AOD1B products generated with surface pressure data from ECMWF analyses and OMCT output (SPNIB, left) and with ECMWF analysis surface pressure and IB assumption (SPIB, right), both compared to the result obtained applying the standard AOD1B RL04 product.

This AOD1B time series should also avoid any bias and other artificial signals in the resulting mass variations due to the change in the meteorological data in January 2001. To check the latter, data from 2001 were analysed where OMCT ocean bottom pressure, i.e., the superposition of atmospheric surface pressure and simulated pressure of the local baroclinic water column, as well as surface pressure data over land are available from both operational ECMWF analyses and ERA40 re-analyses. Therefore, for 2001 corresponding AOD1B products have been derived from operational ECMWF analyses and OMCT simulations (e.g., OMCT output combined with VI, OMCT output combined with SP, SP over land plus IB over the oceans) and, for comparison, from an OMCT run forced with ERA-40 combined with ERA-40 SP (ERNIB). As for the standard GRACE product, the mean fields were created over the period 2001-2002. Figure 4 shows that a) with an AOD1B product including OMCT output data the seasonal signal is significantly reduced; b) VI can be substituted by simple SP; and c) the difference between operational and ERA-40 surface pressure can be neglected. Consequently, the already available AOD1B products for CHAMP and GRACE mission data analysis can be prolonged back to 1976 by applying ERA-40 reanalyses and corresponding OMCT simulations.

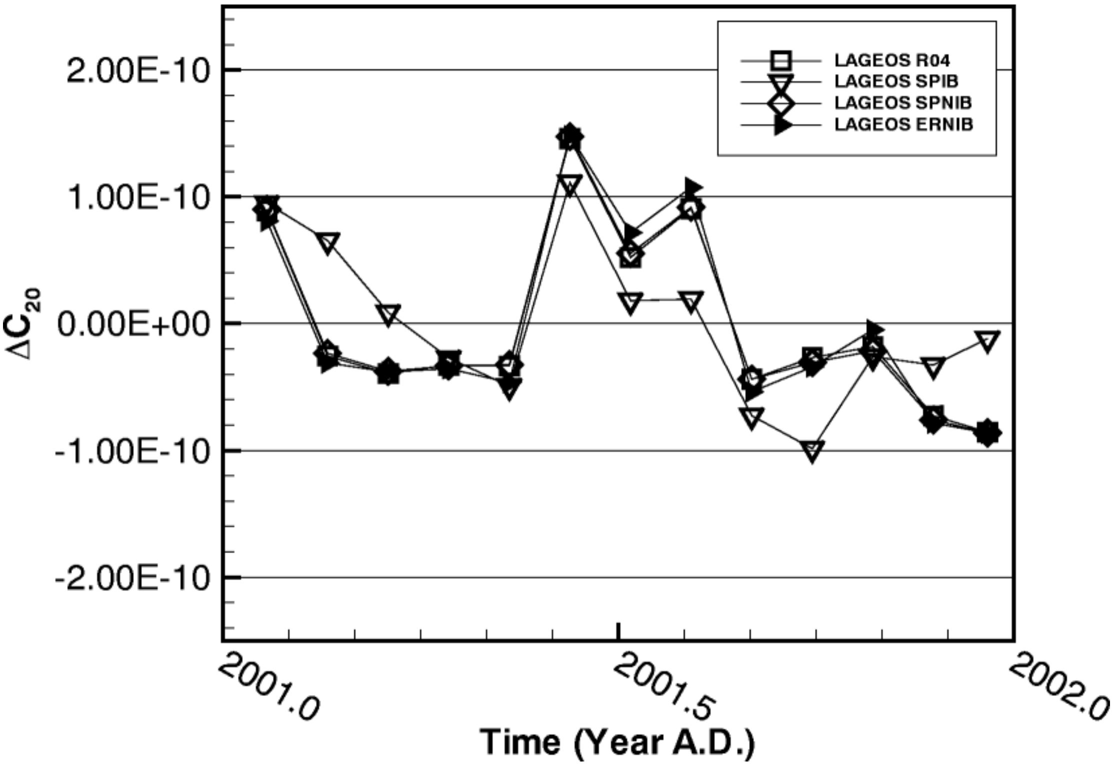

Fig. 4 C_{20} variability for 2001 derived from LAGEOS using different AOD1B products (R04: standard Release 04 AOD1B (OMCT output plus vertical integrated pressure, both based on operational ECMWF analyses); SPIB: operational ECMWF surface pressure over land plus IB assumption over the oceans; SPNIB: surface pressure combined with OMCT output, both based on operational ECMWF analyses; ERNIB: ERA40 surface pressure combined with ERA40 based OMCT output).

Figure 5 (left) shows exemplarily the resulting 6-hourly atmospheric plus oceanic AOD1B C_{20}-variability and the corresponding annual plus semi-annual fit for the time period 1976-2007. Figure 5 (right) zooms into the transition from ERA40 (2000) to analysis data (2001). Obviously the mixture in the meteorological forcing, the mean field over the period 2001-2002 used for GRACE-processing as well as the processing simplifications for LAGEOS does not produce any conspicuousness such as bias, drift or artificial signals in the extended solution. The clear annual signal in these time series shows a high correlation of 0.87 for 1993-2006 with LAGEOS results obtained without applying an AOD1B (Table 1). The annual amplitudes and phases are 1.12 10^{-10} and 0.83 10^{-10} and Feb. 13 and Mar. 2, respectively.

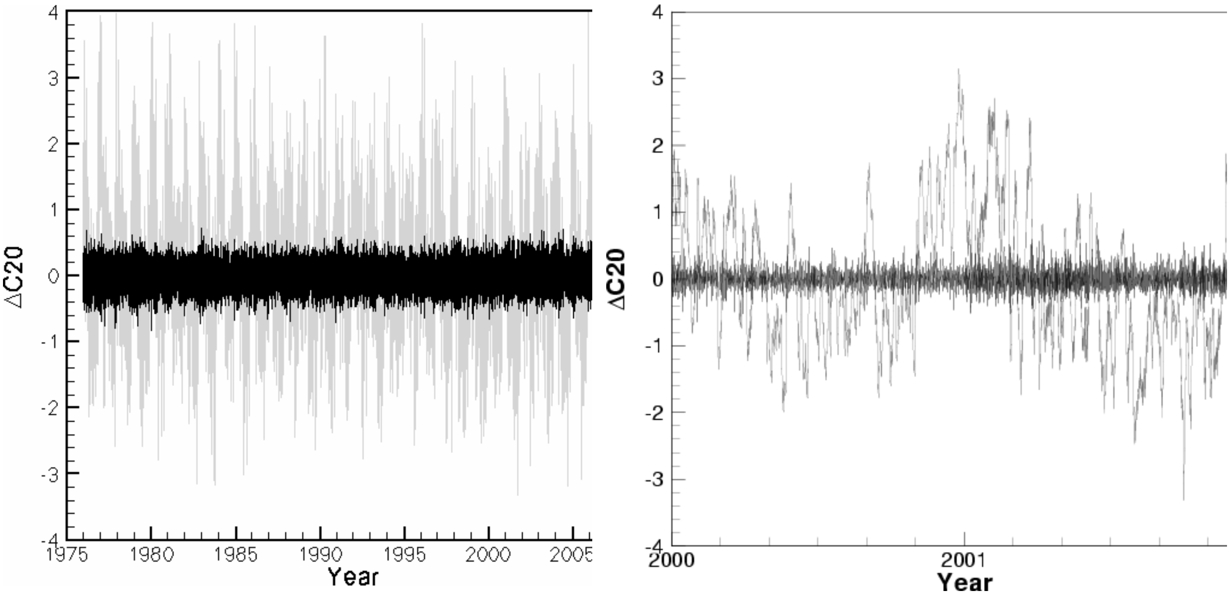

Fig 5 Atmospheric plus oceanic AOD1B C_{20}-variability (*10^{-10}) for the time period 1976-2007 (left). Zoom into the transition from ERA40 to analysis data on January 1, 2001 (right). Shown in both cases are the 6-hourly variability (light grey) and the high-pass-filtered values after subtraction of a daily mean (black).

7. Implication of AOD1B on LAGEOS data processing

Exemplarily for the period 1993-2006, different experiments have been performed in order to demonstrate the impact of the application of AOD1B within LAGEOS data processing. This includes the change in correlation of the annual and semi-annual signals as well as the impact on LAGEOS orbits and SLR residuals.

Table 2 shows the correlations of annual plus semi-annual fits between LAGEOS with and without correction of AOD1B, WGHM, AOD1B and GRACE for different periods within 1993-2006. It can be concluded that

- The AOD1B series has been prolongated consistently (at least to 1993) because the difference between the correlations when processing LAGEOS with and without AOD1B is nearly independent from the investigated time period and AOD1B processing philosophy explained above.
- The correlation between the "standard" LAGEOS C_{20} time series processed without applying an AOD1B model and the primarily annual signals of WGHM (hydrology), AOD1B (atmosphere and ocean) and GRACE (hydrology) is very high (0.77-0.94).
- The reduction of (the annual) AOD1B signal in LAGEOS processing reduces the correlation with the above annual time series by 30-50%.
- If LAGEOS and GRACE are fairly compared one by one (both applying AOD1B) for the period 2003-2006 the generally shown good agreement of the annual C_{20} variability of 0.94 is reduced to 0.78 (and even 0.63 when comparing to the full GRACE mission period until end of 2007). This is in opposite to what one would expect, i.e., a better agreement between GRACE and LAGEOS if common standards are applied. In parallel, the correlations to the pure annual signals of WGHM and AOD1B are drastically reduced from

0.77 to 0.37 and from 0.87 to 0.36, respectively. Figure 6 depicts the annual plus semi-annual signals of LAGEOS with and without applying AOD1B for the period 2003-2006 and for comparison also the corresponding GRACE signals. Table 2 summarizes the corresponding amplitude and phase values showing a better agreement between GRACE and the corrected LAGEOS time series for the annual and semi-annual amplitudes as well as for the semi-annual phase. Nevertheless, relevant differences between both time series remain. This proves that an atmosphere/ocean corrected LAGEOS is still sensitive to primarily annual hydrological mass variations, but shows in addition semi-annual signals of unknown nature.

Table 1 Correlations of annual plus semi-annual fits between different data sets (LAG (w/o) = LAGEOS processed without AOD1B; LAG(with) = LAGEOS processed with AOD1B) and data periods (in brackets)

	LAG (with) (1993-2006)	LAG (with) (1993-2000)	LAG (with) (2003-2006)	WGHM (1993-2006)	AOD (1993-2006)	GRACE (2003-2006)	GRACE (8/02-12/07)
LAG (w/o) (1993-2006)	0.76			0.77	0.87		0.94
LAG (w/o) (1993-2000)		0.75					
LAG (w/o) (2003-2006)			0.80			0.94	
LAG (with) (1993-2006)				0.37	0.36	0.78	0.63

Table 2 Annual and semi-annual amplitudes and phases for LAGEOS processed with and without applying AOD1B RL04 models and for GRACE for the period 2003-2006

	LAGEOS (w/o AOD1B)	LAGEOS (with AOD1B)	GRACE
Annual amplitude * 10^{-10} [-]	1.38	0.42	0.68
Annual phase [-]	Feb 15	Jan 24	Feb 28
Semi-annual amplitude * 10^{-10} [-]	0.80	0.71	0.40
Semi-annual phase [-]	Oct 12	Nov 6	Nov 13

The unresolved bias between LAGEOS and GRACE (Figure 1) has not been changed significantly when applying the AOD1B model and remains in the order of $2 \cdot 10^{-10}$**.** Also, the influence of AOD1B on the LAGEOS orbits and SLR fits can be neglected. The mean of all SLR residuals for the period 1993-2006 of about 1.73 million observations is in both cases, i.e., with and without applying AOD1B, 0.16 mm, and the standard deviation 11.5 and 11.6 mm, respectively. The orbit differences in positions of 39 LAGEOS-1 and LAGEOS-2 weekly arcs with 120s spacing in 2004 (approximately 200.000 values) show 12 and 14 mm RMS. Similar results have been found for JASON and GRACE. Nevertheless, the authors believe that these results depend much on the parameterization of the arcs. Edge effects of the dynamical solution largely drive the maximum orbit differences, therefore they should not be considered as a proper indication of the AOD1B influence.

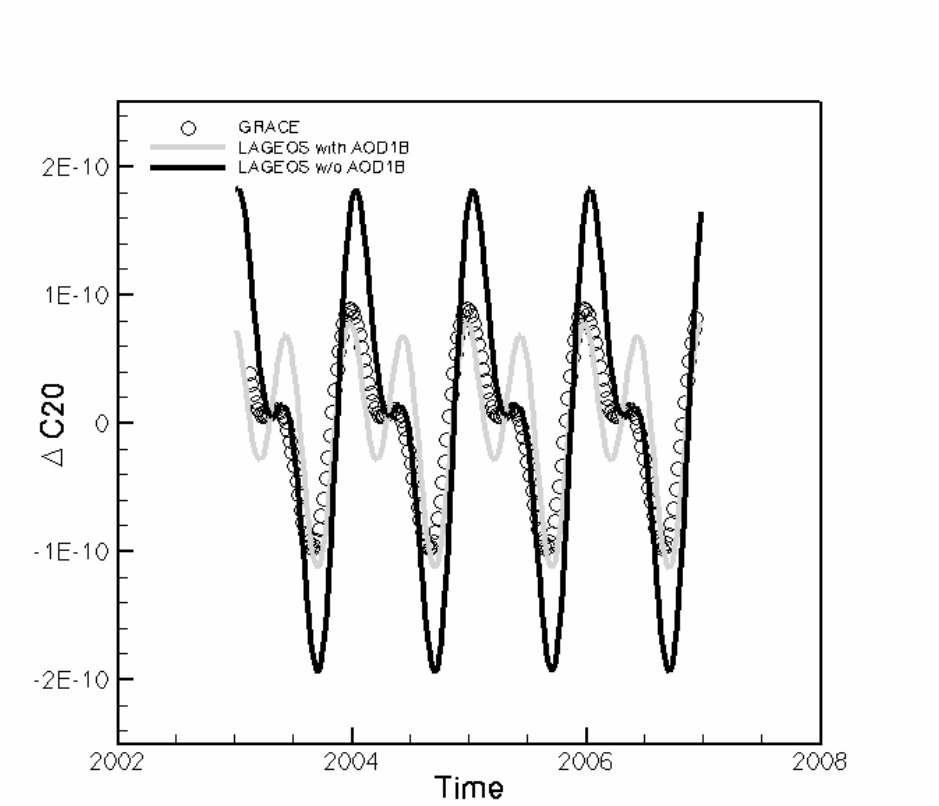

Fig 6 Annual plus semi-annual C_{20} variations for the period 2003 till 2006 derived from weekly LAGEOS data analysis without (black) and with applying AOD1B (grey) time series and from GRACE (dots). For better representation the high-frequency LAGEOS and GRACE signals are not shown

Conclusions

It has been shown that the LAGEOS-derived C_{20} coefficient of the Earth geopotential is significantly affected by short-term circulation induced mass redistributions in the atmosphere and oceans. Taking into account the AOD1B correction model already available for the GRACE mission period both annual and semi-annual time series (with and without AOD1B) are still highly correlated (0.80), but the annual amplitude decreases by about 70 %. The reduction of the seasonal signal and the more consistent comparison with CHAMP, GRACE or GOCE, leads to the conclusion that AOD1B products have to be taken into account when evaluating LAGEOS data. Therefore, the AOD1B time series has been prolongated back to the advent of LAGEOS-1 in 1976 with slightly different processing standards compared to the model generated for GRACE data reduction. By means of sensitivity studies it has been demonstrated that for LAGEOS data exploitation the vertical integrated pressure can be substituted by surface pressure. Further, the simulation tests showed that the substitution of the operational data by ERA-40 re-analyses does not produce any systematic error or jump in the time series. The implication of the AOD1B model on LAGEOS data processing results has been investigated for the period 1993 till 2006. The major findings are that a) the unresolved bias between LAGEOS and GRACE has not been changed significantly when applying the AOD1B model and remains in the order of $2 \cdot 10^{-10}$**;** b) the influence of AOD1B on the LAGEOS SLR (and K-band for GRACE) fits and orbital fits can be neglected; c) the correlation between the “standard” LAGEOS C_{20} time series processed without applying an AOD1B model and the primarily hydrological or atmospheric annual signals of WGHM, AOD1B and GRACE is very high (0.74-0.95), d) the reduction of AOD1B signal in LAGEOS processing reduces the correlation with the above annual time series by 30-50% and e) the reduced correlation between LAGEOS and GRACE is in opposite to what one would expect, i.e., that a better agreement between GRACE and LAGEOS will be observed if common standards are applied. The latter leads to the conclusion that a short-term non-tidal atmosphere/ocean corrected LAGEOS solution is not only sensitive to primarily annual hydrological mass variations, but also to semi-annual additional seasonal signals of unknown nature. Taking into account the longer AOD1B model time series these residual signals can now be studied in more detail. Additionally, it should be investigated in the near future if the AOD1B model needs to be applied when processing other geodetic satellites such as AJISAI, STARLETTE and others.

Notes:

- The operational AOD1B RL04 products based an ECMWF analysis data for the period 2001 until present and the AOD1B RL04 products before 2001 based on ERA40 data are available at the Information System and Data Center (ISDC) at GFZ Potsdam (http://isdc.gfz-potsdam/grace).
- Details on the operational RL04 products as well as on the precursor releases can be found in the AOD1B Product Description Document for Product Releases 01 to 04 (Rev. 3.1, April 13, 2007) which can be downloaded at ISDC.
- A quality monitoring page for the period 2001 until present is available at http://www-app2.gfz-potsdam.de/pb1/op/grace/results.
- Corresponding plots for the period before 2001 are given in the appendix.

Acknowledgements:

- This work was done within the BMBF (German Ministry for Education and Research) Geotechnologien research and development programme under grant 03F0423.
- We thank ECMWF for provision of meteorological data necessary to generate AOD time series.

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Appendix

In order to check the quality of the AOD1B products different plots have been generated and are shown in the following. First, the minimum, maximum, mean and wRMS (cosine latitude weighted RMS) geoid height variability with respect to a 2001+2002 mean field for all four data types

- ATM: variability of the vertical integrated atmosphere
- OCN: variability of mass distributions in the water column as simulated with OMCT
- GLO: variability of the global combination of atmosphere and ocean (GLO = ATM + OCN)
- OBA: variability of the OMCT ocean bottom pressure

and for the complete production period 1976 until today (using the ERA40 derived AOD1B products up to 2000 and then the operational analysis data based AOD1B products) is derived from the spherical harmonic coefficients up to degree and order 0 to 100. Second, the individual degree 0 to 2 spherical harmonics 6-hourly time series for the "atm", "ocn", "glo" and "oba" variability are shown in grey and high pass filtered (after subtraction of the daily mean) in black.

Generally, for a "nominal" AOD1B product based on GRACE experience for 2001-today the

- mean geoid "atm" variability should be close to zero (due to subtraction of a long-term 2001+2002 mean) and should show an annual signal (Fig. A-1, top left).
- mean variability of the “ocn” C00 time series (Fig. A-2, top right) must be close to zero because a mass conserving approach has been used in the RL04 OMCT runs (Fig. A-1, top right);
- minimum and maximum "atm" and "ocn" variability should be generally below 20-25 mm geoid height (Fig. A-1, top);
- minimum and maximum "glo" geoid height variability should be slightly smaller than for "atm" due to the quasi compensation of "atm" plus "ocn" over the oceans (Fig. A-1, bottom left);
- "oba" results should show smaller minimum and maximum geoid height variability compared to "glo" because for "oba" the land pixels have been set to zero (and therefore have no variability) (Fig. A-1, bottom right);
- weighted rms for all four geoid height variability components should be about 2-4 mm geoid height;
- high pass filtered Cnm and Snm should show no jumps in amplitude.

The extended time series back to 1976 fulfils these “requirements” with the following exceptions:

- The OCN component of C00 shows a small slope. But this can be neglected because of the 10 times smaller scale compared to other coefficients.
- The high pass filtered ATM component of C00 shows a decreasing scatter with time. This is likely due to increased quality of ERA40 with time; also the superiority of analysis data since 2001 becomes obvious.
- The C11 and S21 OCN components show a small slope between 1976 and 2000, what principally can be caused by artificial, i.e., numerical effects or

realistic ocean mass redistribution. However, these effects are not separable by simple time series analyses.

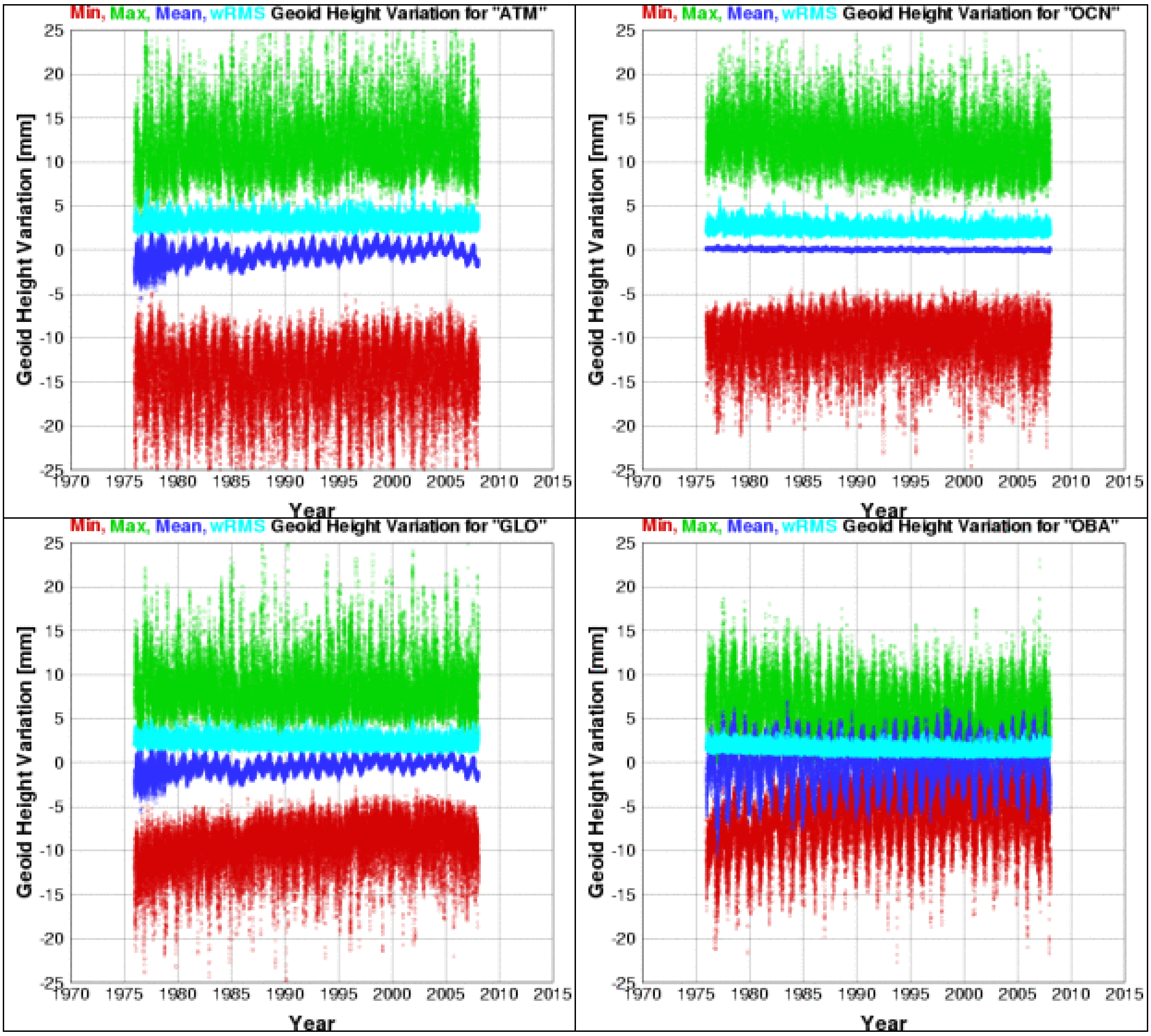

Figure A-1: Minimum, maximum, mean and wRMS geoid height variability [mm] for AOD1B RL04 components "atm", "ocn", "glo" and "oba" up to degree and order 100, including degree 0 and 1, since January 1, 1976.

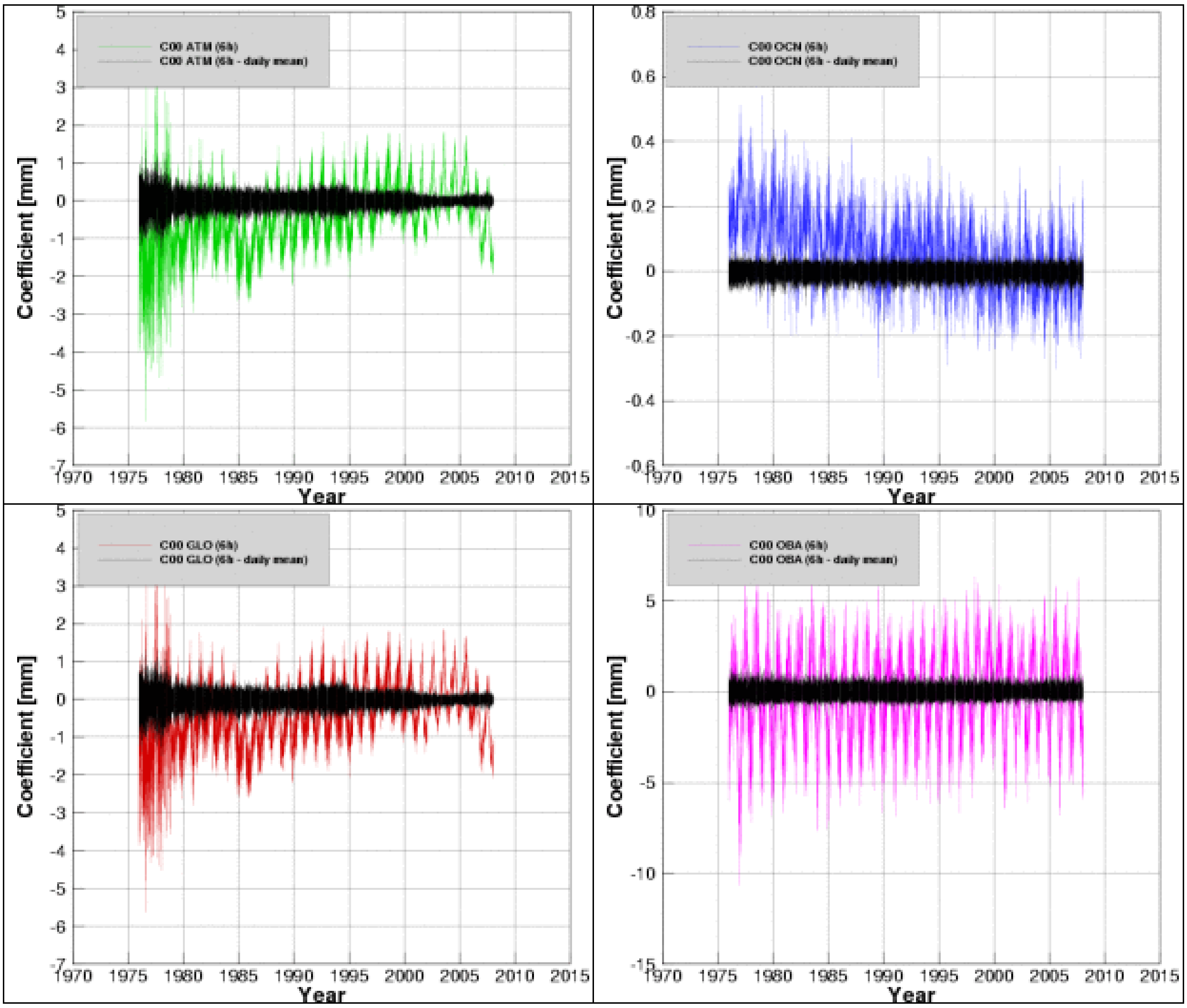

Figure A-2: C00 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

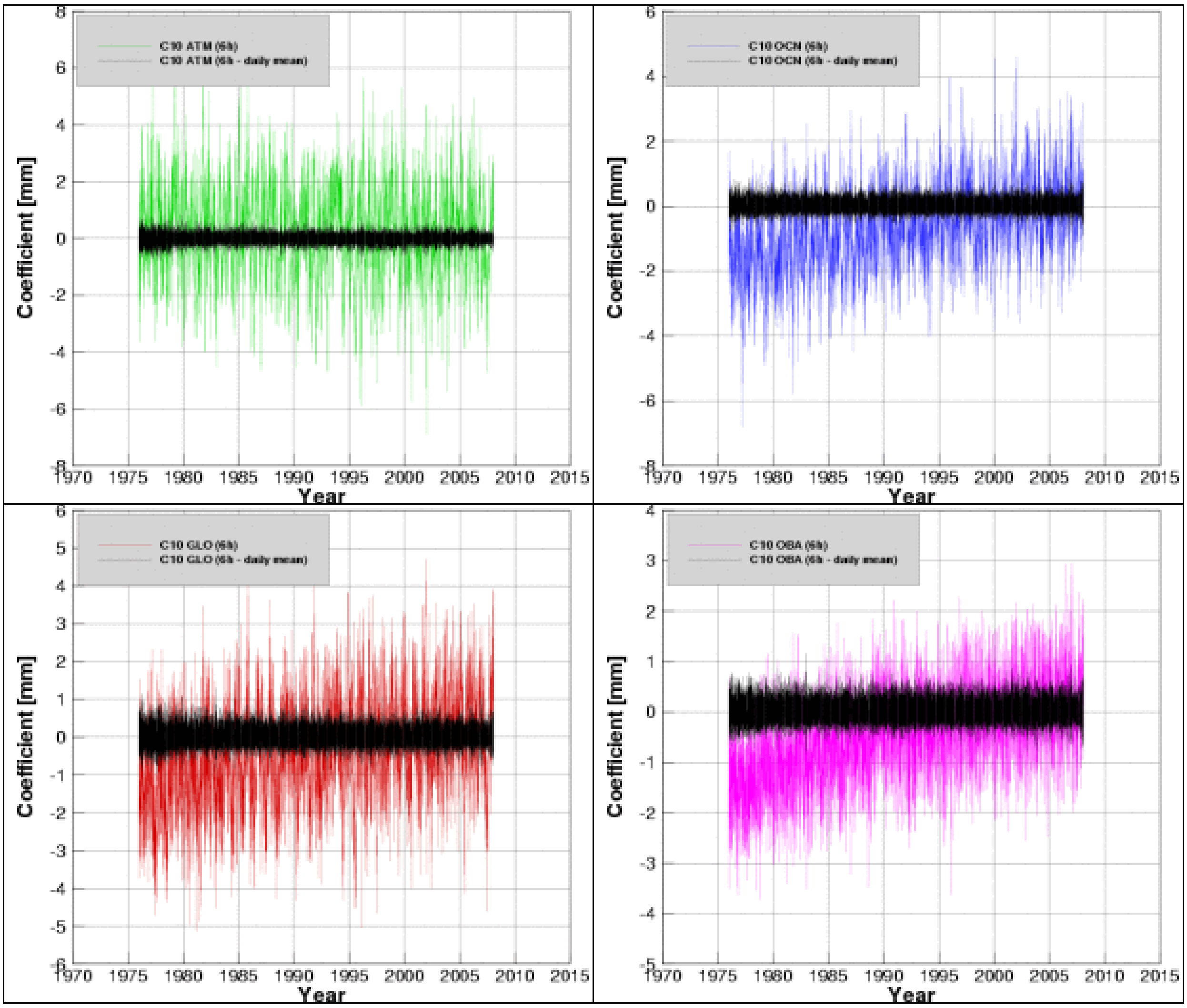

Figure A-3: C10 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

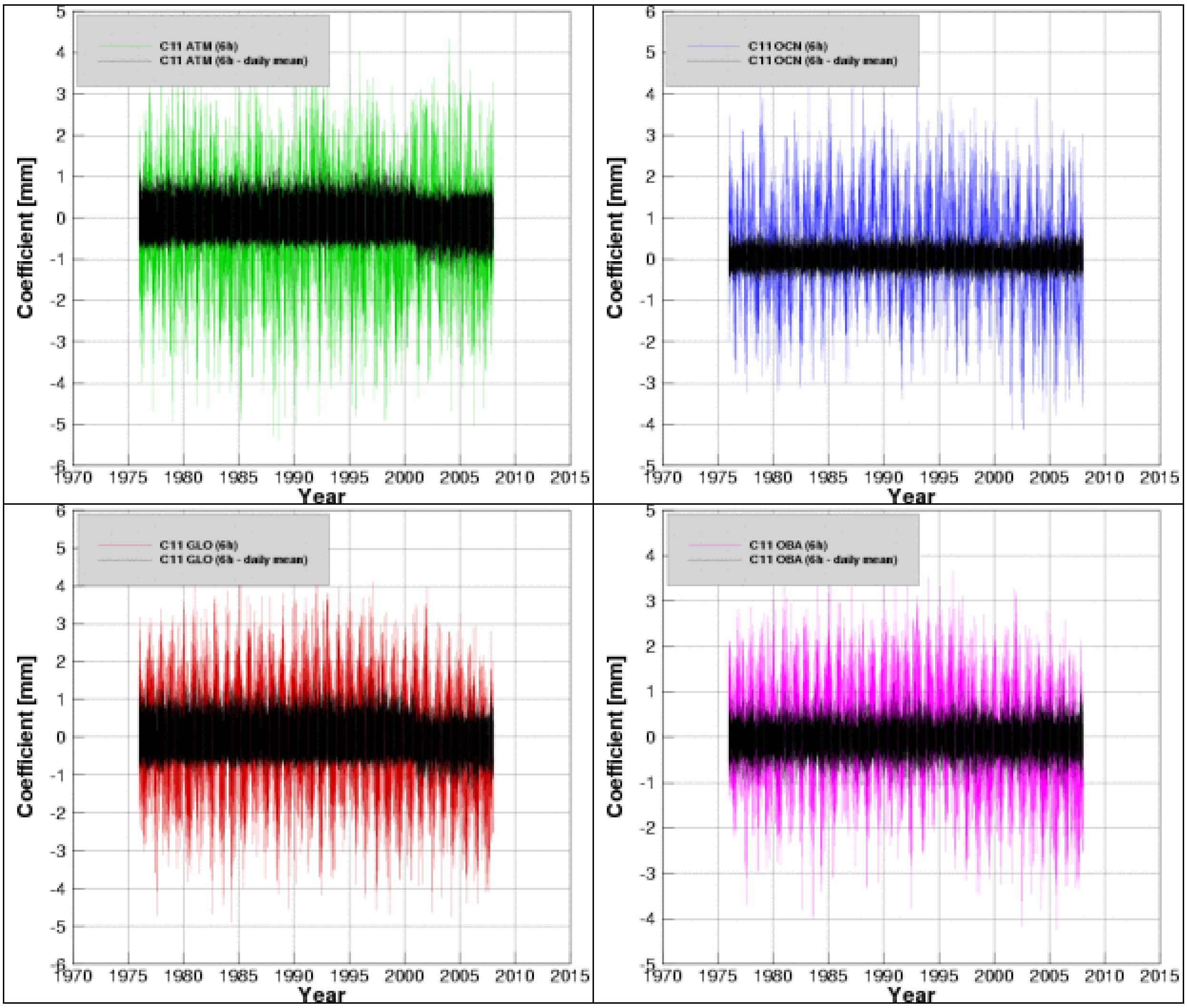

Figure A-4: C11 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

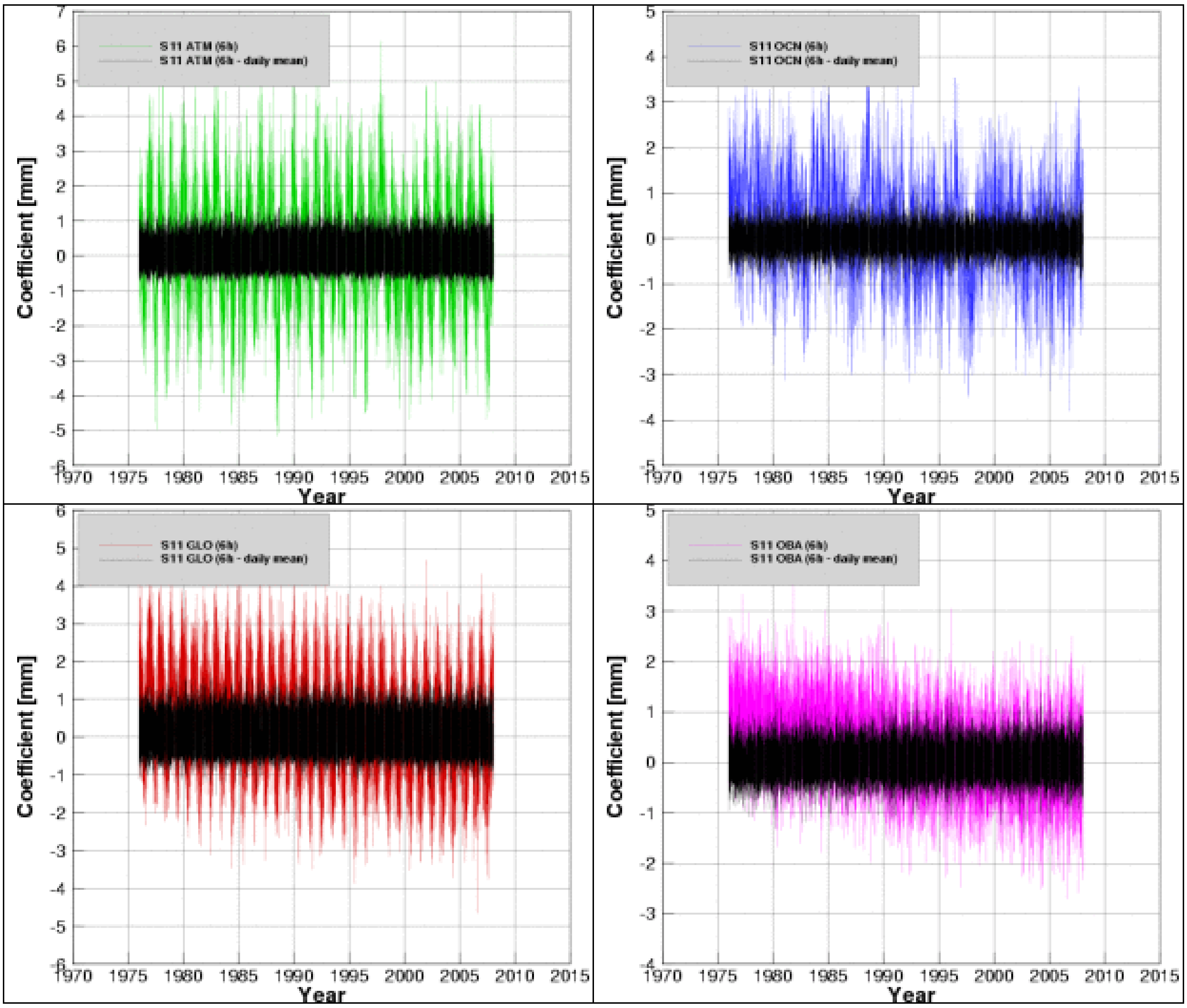

Figure A-5: S11 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

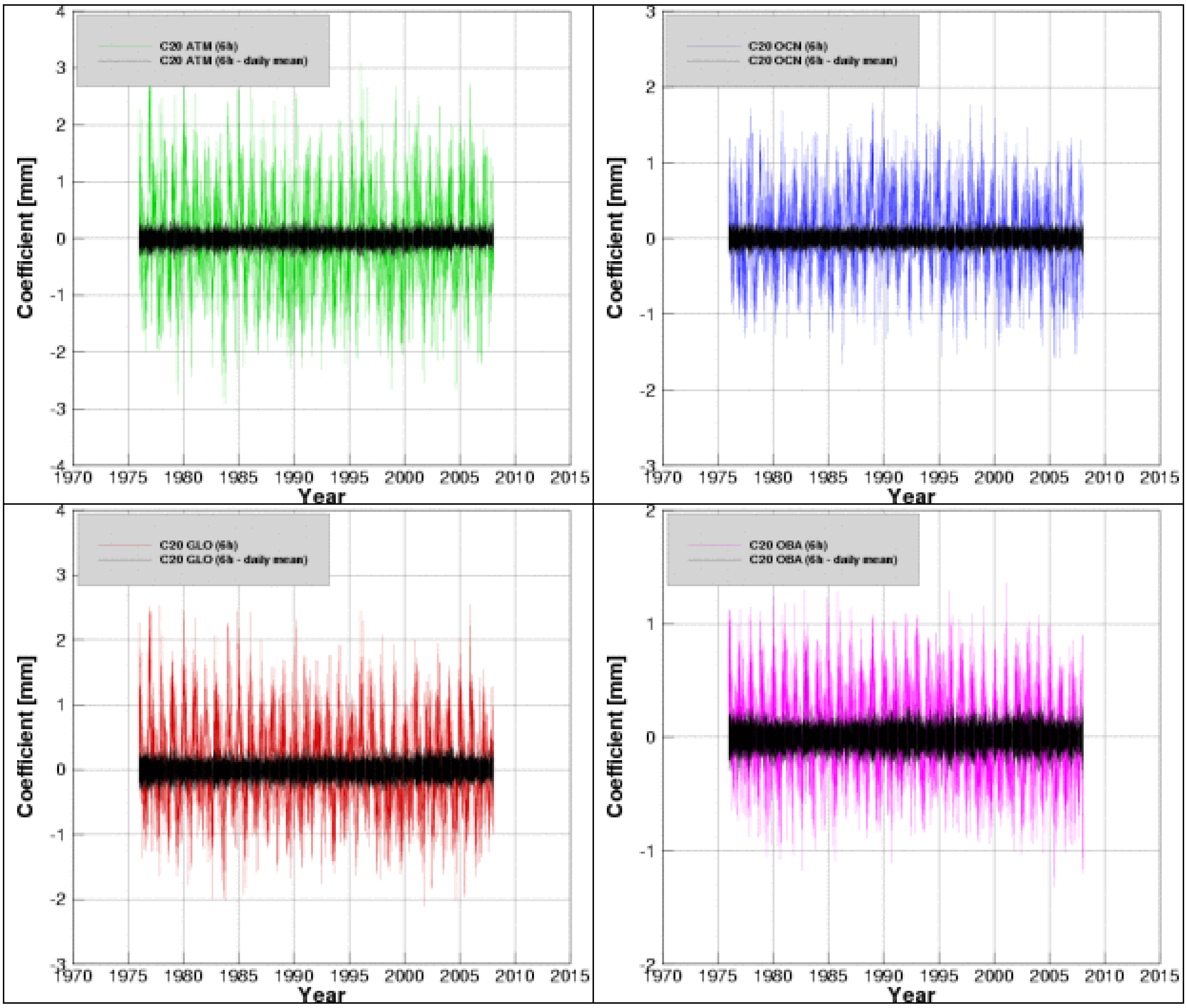

Figure A-6: C20 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

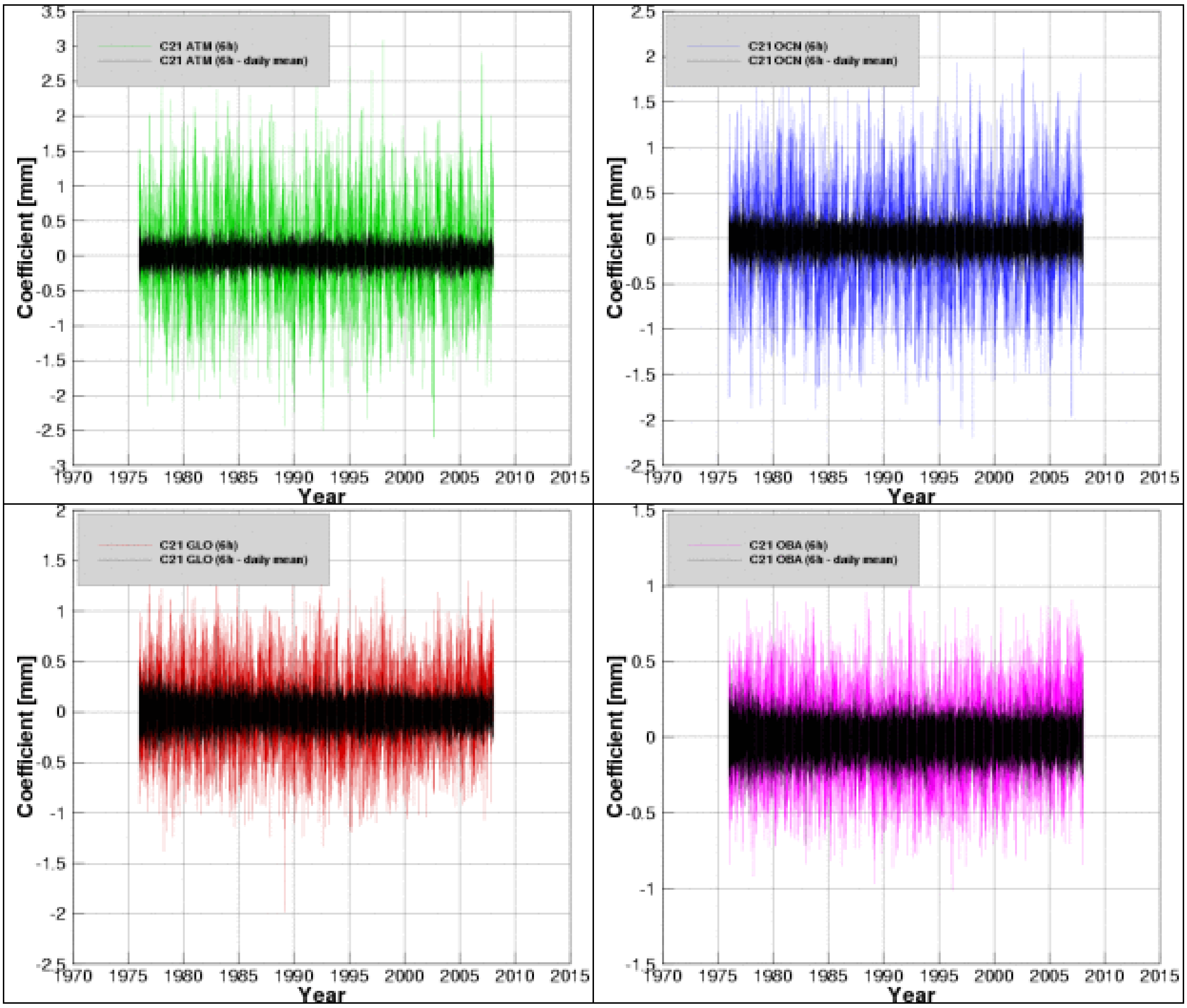

Figure A-7: C21 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

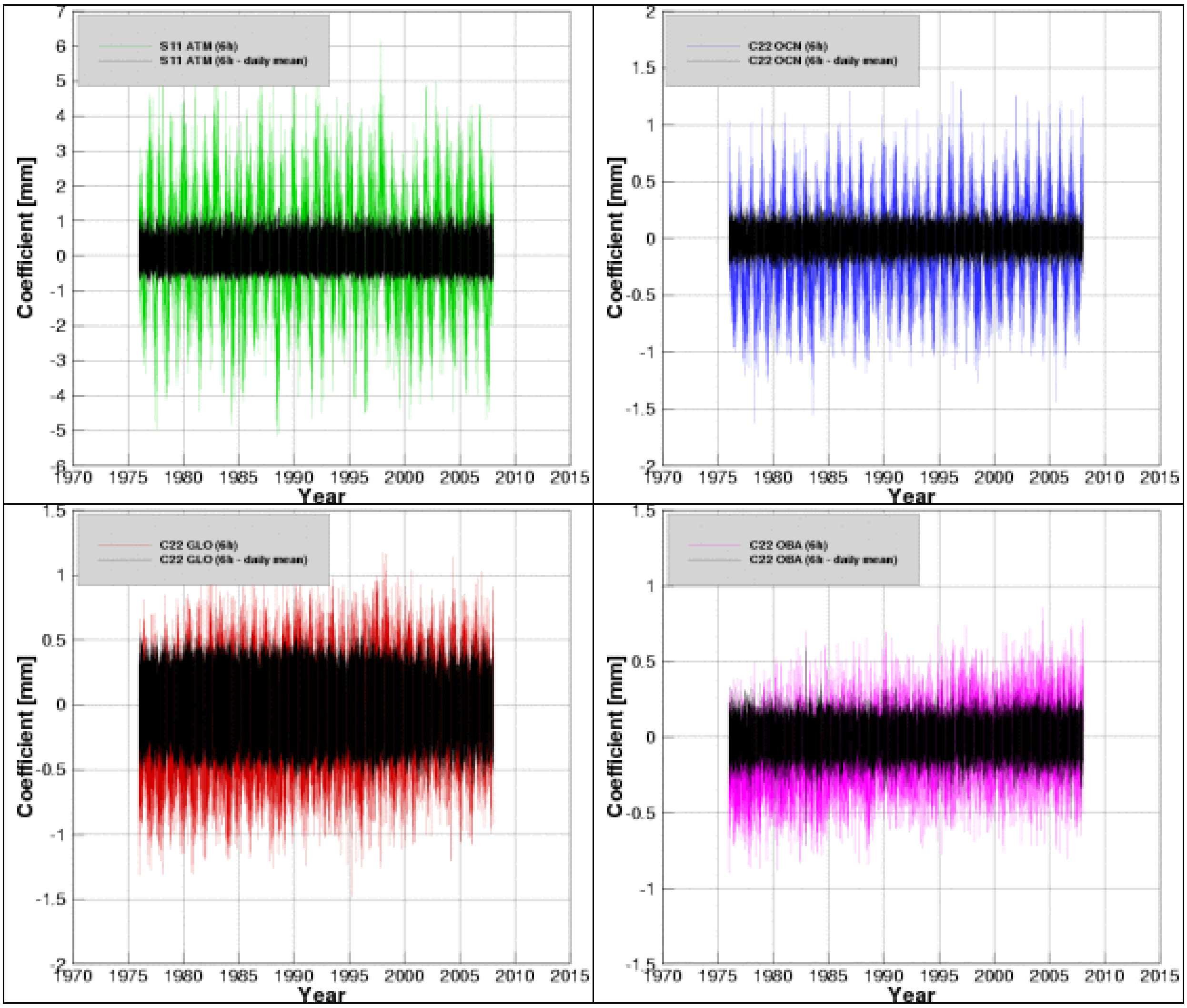

Figure A-8: C22 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

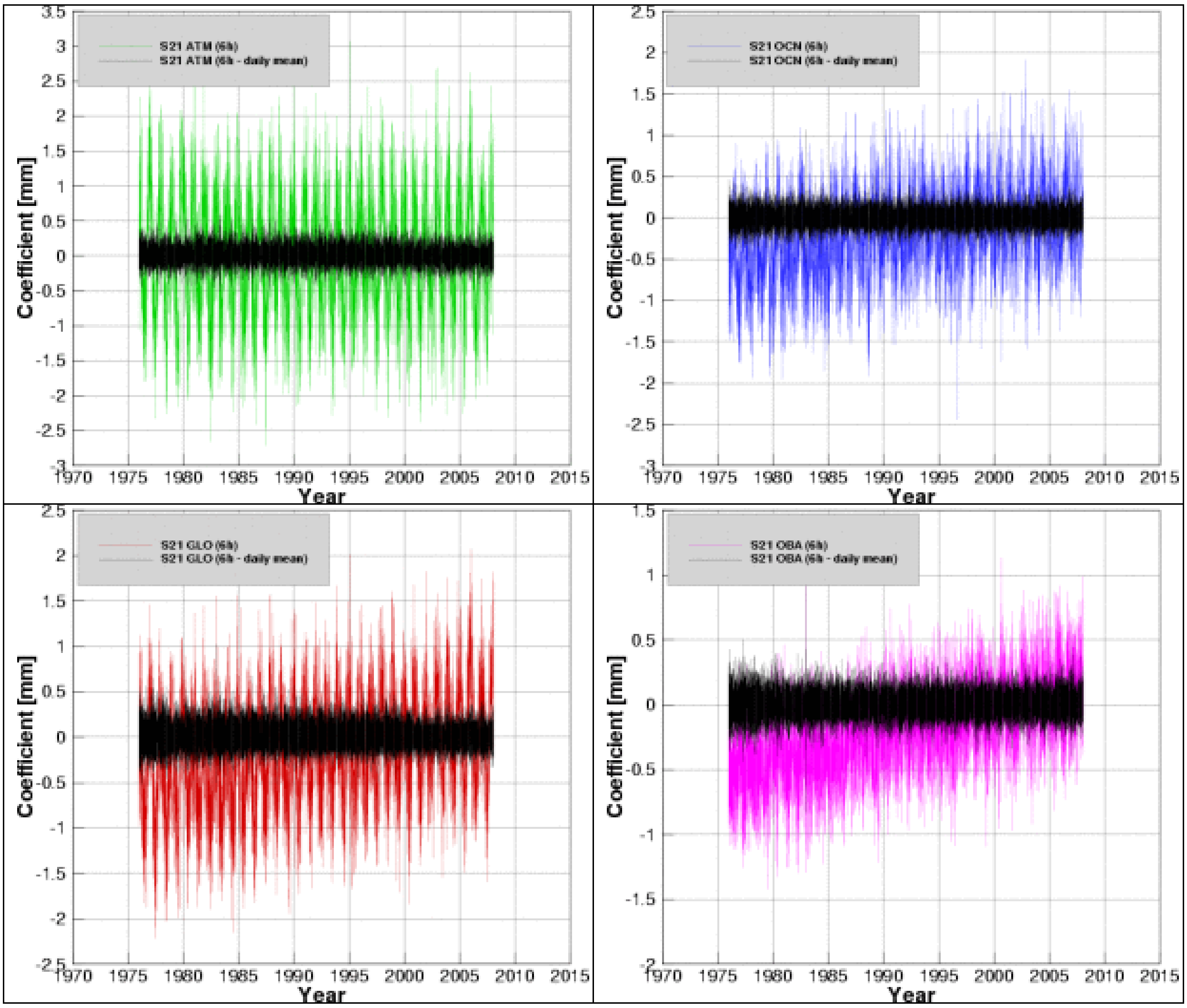

Figure A-9: S21 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

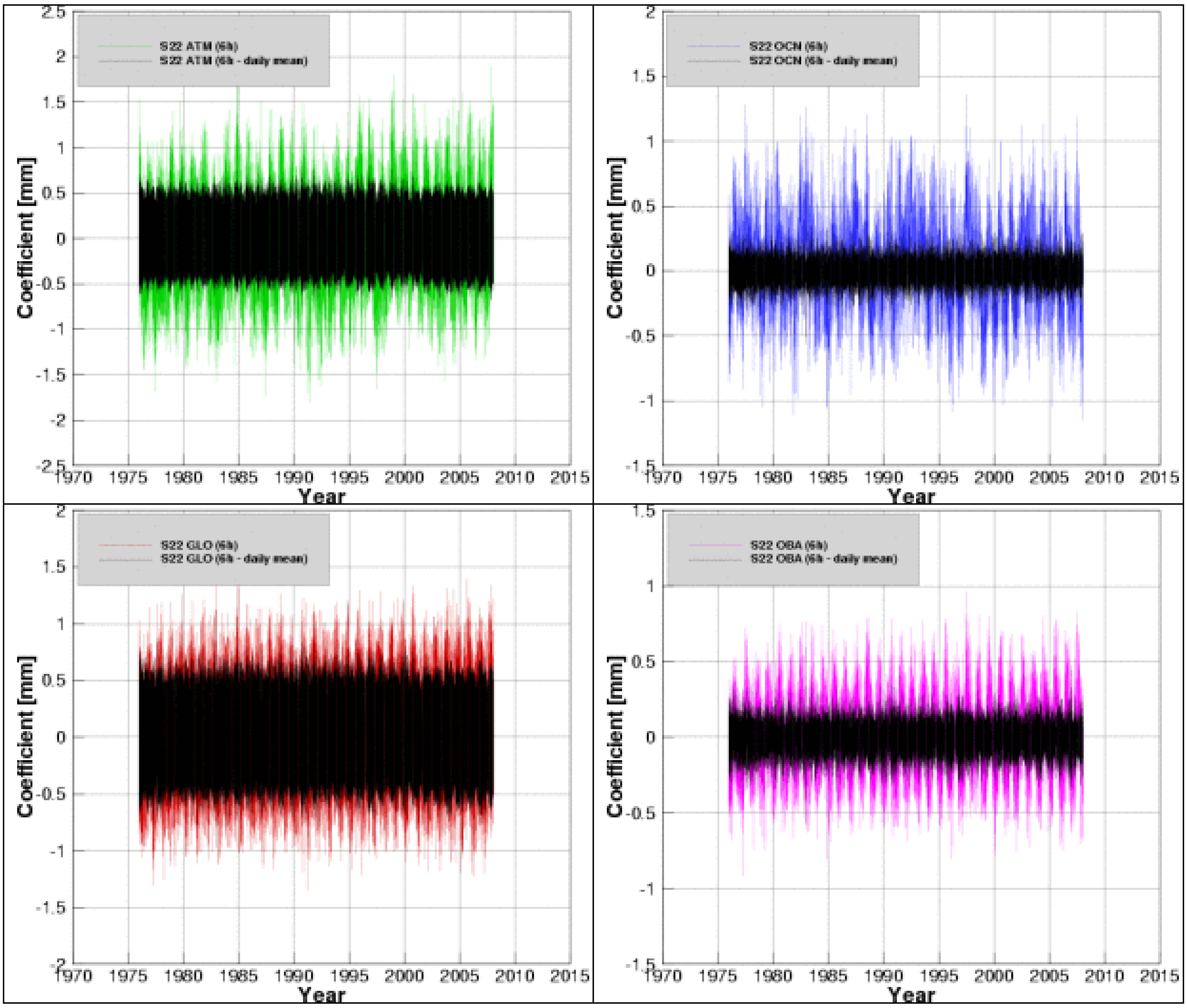

Figure A-10: S22 spherical harmonics 6-hourly time series in terms of geoid height variability [mm] for the "atm", "ocn", "glo" and "oba" variability in grey and high pass filtered (after subtraction of the daily mean) in black.

ISSN 1610-0956

Frank Flechtner, Maik Thomas, Rolf König, A long-term model

STR08/12