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Correction of inconsistencies in ECMWF's operational analysis data during de-aliasing of GRACE gravity models

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SUMMARY

The main objective of the Gravity Recovery and Climate Experiment (GRACE) Atmospheric and Oceanic De-Aliasing Level-1B product (AOD1B) is the removal of high-frequency non-tidal mass variations due to sub-monthly mass transport in the atmosphere and oceans. Application of AOD1B shall avoid aliasing of these high-frequency signals into monthly gravity models derived from modern gravity missions and shall help to derive consistent orbit solutions for altimetry and Satellite Laser Ranging missions. The AOD1B 6-h series of spherical harmonic coefficients up to degree and order 100 are routinely generated at the German Research Centre for Geoscience and distributed to the GRACE Science Data System and the user community. Inputs for this product are acquired from numerical weather prediction models which are regularly revised and consequently not stable in time. The latest AOD1B release 5 (RL05) is based, as all other releases, on input from ECMWF and does not resolve this problem of discontinuities present in the surface pressure and surface geopotential input data. This might contaminate the gravity field variations derived from atmospheric mass variations. In this paper we present a method to overcome this problem during future AOD1B product generation, as well as two new Level-2 products (GAE and GAF) that, over land, fix *a posteriori* the two jumps present in the already distributed Level-2 RL05 monthly gravity models which were based on AOD1B RL05. The impact of the proposed correction on the variations and long-term trend of the total mass of the atmosphere and on the ice mass balance over Antarctica and over Greenland is also illustrated. We found that the GAE/GAF-corrected trend of the global atmospheric mass over the GRACE mission lifetime significantly decreased from -0.05 to -0.02 mm yr^{-1} in terms of geoid height. A considerable effect (33 per cent) was also found in the quadratic term of ice mass loss over Antarctica which results in an acceleration of 3.2 Gt yr^{-1} yr^{-1} smaller than without applying this correction.

Key words: Satellite geodesy; Time variable gravity; Glaciology.

1 INTRODUCTION

Temporal variations of the Earth's gravity field as observed by low-Earth orbiting satellites such as CHAMP, Gravity Recovery and Climate Experiment (GRACE) or the upcoming GRACE-FO (Follow-on), are caused by mass redistribution within the system Earth (Tapley *et al.* 2004). High-frequency non-tidal mass variations due to sub-monthly mass transport in the coupled atmosphere–ocean system cause time-varying gravitational forces acting on the orbiting satellites. Observations from gravity missions are collected and accumulated over several days in order to produce gravity field solutions covering the whole globe with reasonably high spatial resolution (Wahr *et al.* 1998). The nominal accumulation period of GRACE is 30 d, but can also be as short as a few days on the expense of a much reduced spatial resolution. However, the ground track sampling rate of polar missions at low altitudes of around 450 km like GRACE is too limited and therefore inadequate to directly measure non-tidal high-frequency mass variations present in the atmosphere and the ocean. In other words, a sampling rate above the Nyquist frequency—which is the lower bound for the sampling rate for alias-free signal sampling—is not possible under these conditions. Consequently, fast-changing atmospheric and oceanic masses will cause temporal aliasing effects in the estimated gravity solutions (Han *et al.* 2004; Wahr *et al.* 2004). One way to avoid aliasing is to model these variations from external information as output of meteorological and ocean models, and to apply them during the gravity field determination process as de-aliasing background models. The independent knowledge of these atmospheric and oceanic mass transport components is also needed in order to separate individual contributions from the GRACE gravity models and, for example, to extract hydrological (e.g. Rodell & Famiglietti 2001; Ramillien *et al.* 2004; Schmidt *et al.* 2008) or glaciological signals (e.g. Velicogna & Wahr 2006; Horwath & Dietrich 2009; Groh *et al.* 2014).

German Research Centre for Geoscience (GFZ) is routinely computing Atmospheric and Oceanic De-Aliasing Level-1B (AOD1B) products that fulfill the above-mentioned requirements (Flechtner *et al.* 2014). The two objectives of AOD1B are hence (1) to avoid aliasing during daily GRACE Precise Orbit Determination (POD) and (2) to separate the atmospheric and oceanic contributions from other signals (hydrology, ice and solid Earth) in the monthly gravity solution. The AOD1B products are publicly available at GFZ's Information System and Data Centre. The most recent AOD1B Release 05 (RL05) is a set of 6-h spherical harmonic coefficients up to degree and order 100 that is provided for the period 1979 January 1 till today and updated on an approximately weekly basis. Up-to-date information on the status of this product can be obtained from the web-pages at www.gfz-potsdam.de/AOD1B. The basis of the oceanic part is the Ocean Model for Circulation and Tides (OMCT; Thomas *et al.* 2001), which has been improved for AOD1B RL05 in terms of both parametrizations and spatial resolution (Dobslaw *et al.* 2013). For the atmospheric part as well as for the atmospheric boundary conditions required for the ocean model, which includes atmospheric pressure, surface winds, heat and freshwater fluxes, the necessary input data (surface pressure, surface geopotential and vertical profiles of temperature and specific humidity) are extracted from the European Centre for Medium Range Weather Forecast (ECMWF) archives. The early AOD1B RL05 products for the period 1979–2001 are based on the ECMWF global atmospheric reanalysis data set ERA-Interim. The operational de-aliasing products for the GRACE period from 2001 till present are based on ECMWF atmospheric operational analyses data, that is, data from a numerical weather prediction model, which is intended to provide best possible state estimates and corresponding medium-range forecasts to its users. Currently at ECMWF a four-dimensional variational data assimilation procedure is used (Klinker *et al.* 2000; Mahfouf & Rabier 2000; Rabier *et al.* 2000; Andersson & Thépaut 2008). From time to time the ECMWF is upgraded to incorporate improvements in the physical model, the numerics, the data assimilation scheme and to accommodate new observing technologies as well as an increased number of observations. Those changes to the model consequently may lead to inconsistencies in the time series of operational analysis data. The evolution of the ECMWF analysis and forecasting system from 1985 January to the current date is documented at http://old.ecmwf.int/products/data/technical/model_id. Trenberth (1992) has already shown that trends in the ECMWF atmospheric surface pressure data are impacted by system changes in the operational analysis. Consequently, any error or uncertainty left in the external atmospheric (and oceanic) model data will propagate via the AOD1B product into and deteriorate the monthly gravity field solutions. For instance, at ECMWF the horizontal and vertical resolutions of surface pressure as well as of surface geopotential data are being improved typically every few years. In 2006 January, the horizontal resolution was increased from a spectral truncation of T511 (39 km grid spacing) to T799 (25 km grid spacing) and the vertical resolution from 60 to 91 levels. In 2010 January, the horizontal resolution increased again to T1279 (15.6 km grid spacing). The current (2015 January) vertical resolution is of 130 levels as introduced in 2013 June. The next upgrade is planned for mid-2015 and expected to be T2047, which corresponds to a grid spacing of about 10 km (Abdalla *et al.* 2013). As a consequence of the horizontal resolution changes in 2006 and 2010, the surface pressure and the surface geopotential time series show two in-homogeneities, which consist of positive and negative jumps between 2006 January 29 18h ($t1^*$) and 2006 January 30 00h ($t1$) and between 2010 January 26 00h ($t2^*$) and 2010 January 26 06h ($t2$). Duan *et al.* (2012) associated these two in-homogeneities with two jumps in the AOD1B Level-2 data GAA (monthly atmospheric gravity variations) and GAC (combined monthly atmospheric and oceanic gravity variations). They analysed the potential impacts over mountain glacier regions with steep topography such as the Qinghai-Tibetan Plateau and the Andes. They estimated biases of about 7 cm equivalent water height (EWH) in the atmospheric mass anomalies, which would probably cause biases of the same magnitude and opposite sign in the GSM solutions. They suggested using the more stable ERA-Interim data or a pre-processing strategy within the GRACE Science Data System (SDS) to correct for these biases. Forootan *et al.* (2014) compared de-aliasing products based on operational and on ERA-Interim models, finding a considerable impact on linear trends and seasonal components of atmospheric masses. Local differences over Central Asia and Greenland reach up to ∼1 cm EWH. However, they analysed the impact on the atmospheric component only and not on the GSM solutions. Since the de-aliasing products are applied during daily GRACE POD, the impact of errors present in these data will be first visible at orbit level. Additionally, monthly GSM grids are produced by applying filtering techniques, whose complexity makes the estimation of the propagated errors not straightforward. These two issues (the error introduced at orbit level and the effect of the adopted filtering technique) are exhaustively discussed within this paper.

The most prominent consequence for AOD1B derives from abrupt changes in the model orography in the ECMWF operational model that directly affect the atmospheric surface pressure via the atmospheric pressure lapse rate. This effect is visible globally, even if over the ocean its magnitude is negligible. Moreover, we recall that any long-term changes in atmospheric surface pressure are typically fully compensated by an inverse-barometrically adjustment of the local sea level (Wunsch & Stammer 1997) in a way that the bottom pressure effect of a long-term atmospheric surface pressure change is zero. In principle, it would need artificial shifts in speed or direction of the surface wind systems to cause regional offsets in ocean bottom pressure, but such effects have not been identified during ECMWF model transitions so far. Therefore, a first-order correction of those artefacts is focused on land applications only.

For an a-posteriori correction of the two jumps in 2006 and 2010 January, we have defined two new Level-2 data sets (called GAE and GAF) which are presented in this paper. They *a posteriori* correct the already available RL05 time series of Level-1B 6-h AOD1B 'atm' (atmosphere only) and 'glo' (global atmosphere and ocean combination) as corrections to the corresponding Level-2 monthly averages GAA and GAC. These new coefficients are estimated by comparing the standard atmospheric coefficients based on ECMWF operational analysis with independently generated coefficients based on the ECMWF ERA-Interim reanalysis. The strategy to derive the necessary monthly mean GAE and GAF products and the consecutive implications to GRACE real data analysis are investigated in this paper and described in the following. Additionally, the impact of the proposed corrections on the variation of the total mass of the atmosphere (AOD1B 'atm' C_{00} coefficient) as well as on ice mass variations over Greenland and Antarctica is presented and discussed.

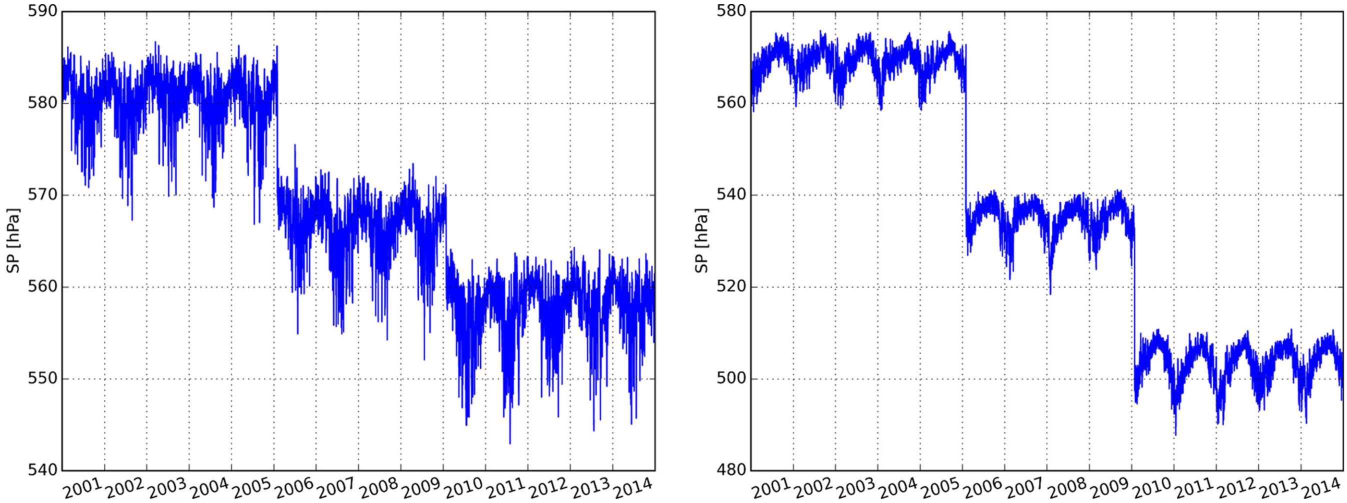

Figure 1. 6-h surface pressure variation between 2001 January and 2014 December at a location over the Andes (latitude −27.24, longitude −68.04) (left) and over Mount Everest (latitude 27.80, longitude 87.00) (right). Two discontinuities are visible in 2006 January and 2010 January.

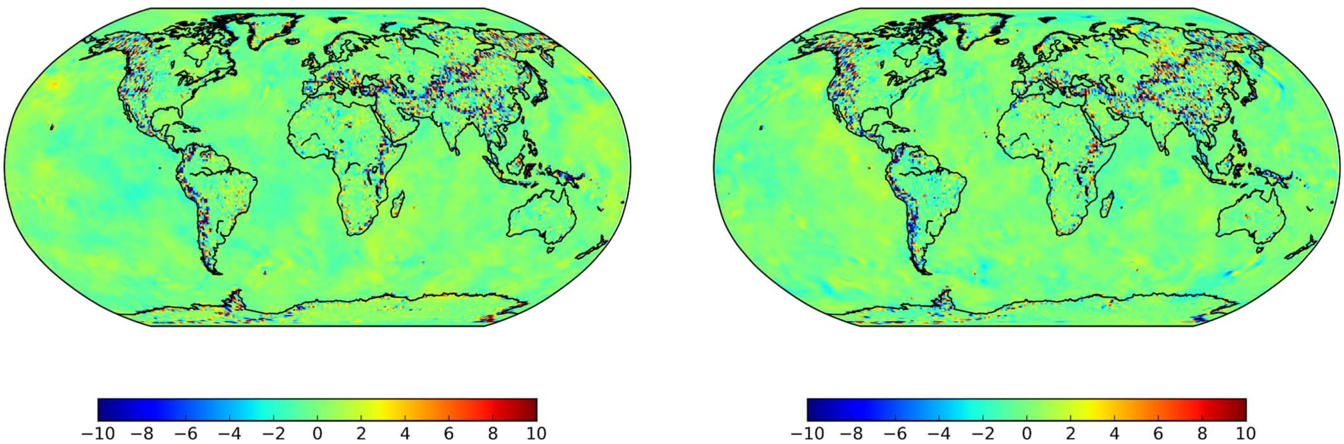

Figure 2. Surface pressure bias [hectopascals] at *t*1 (left) and at *t*2 (right).

Table 1. Statistical information on the surface pressure biases, on GAE, GAF and on the difference of the accurate and intermediate methods.

	Min	Max	Mean	Std
Surface pressure bias at *t*1 [hPa]	−48.3	46.8	−0.01	2.5
GAE [mm]	−88.3	87.5	0.13	9.1
GAE(DDK2)-GAE [mm]	−90.6	76.7	−0.004	7.5
GAE(DDK2)	−16.3	20.6	4.5	−0.05
Surface pressure bias at *t*2 [hPa]	−65.9	65.2	−0.06	2.5
GAF [mm]	−161.3	111.1	0.06	13.5
GAF(DDK2)-GAF [mm]	−115.9	140.7	0.02	11.4
GAF(DDK2) [mm]	−30.1	23.1	6.2	−0.7
Methods difference 2010 January [mm]	−5.5	6.2	−0.01	1.1
Methods difference 2010 February [mm]	−3.8	6.8	−0.01	0.7

2 METHOD

The two jumps present in the surface pressure and surface geopotential from the ECMWF operational archive are mostly localized over land and at high altitudes in mountainous regions. Fig. 1 shows for two points over the Andes and the Mount Everest a decrease in the surface pressure time series. Comparing the surface pressure variations at $t1$ ($t1$ minus $t1^*$) and at $t2$ ($t2$ minus $t2^*$) from the operational and the reanalysis data, we are able to estimate the biases present in the operational time series (Fig. 2). The estimated biases have a range (difference between min and max values) of ∼85 hPa at $t1$ and of ∼130 hPa at $t2$ (Table 1) and a dipole pattern characteristic around mountain peaks (Fig. 2), whose error would be partially averaged out by block mean computation. In fact, the higher resolution of the ECMWF orography model is getting closer to the mountain contours and is able to depict mountain peaks (high elevation

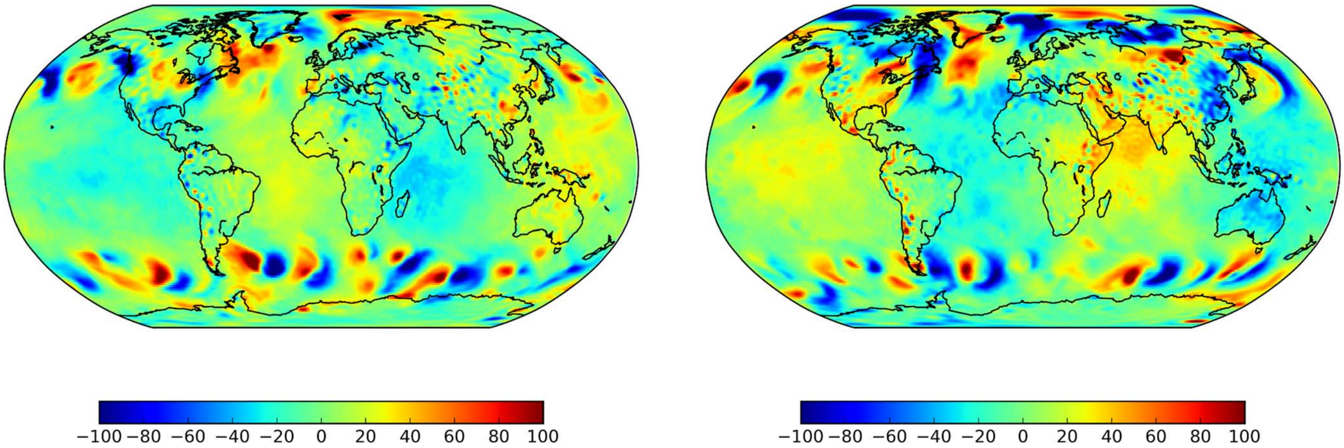

Figure 3. Atmospheric gravity variations derived from operational data at *t*1 (left) and *t*2 (right) in millimetre EWH. Jumps appear as red and blue spots over land areas.

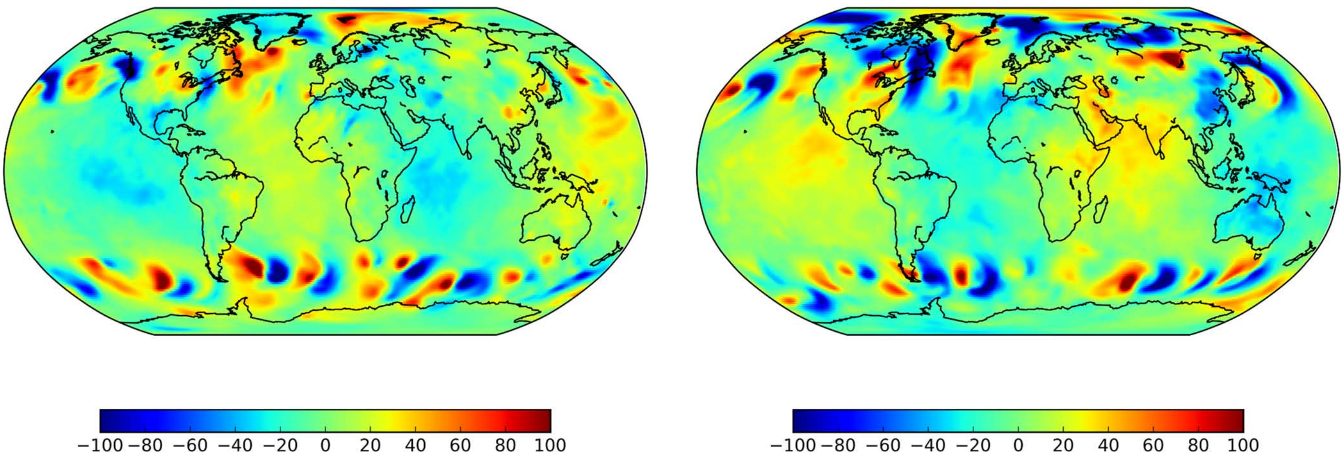

Figure 4. Atmospheric gravity variations derived from reanalysis at *t*1 (left) and *t*2 (right) in millimetre EWH.

points) and valleys (low elevation points between peaks) that in a lower horizontal resolution are averaged out. The peaks correspond to lower pressure (negative jumps) and the valleys to higher pressure (positive jumps). If not corrected, the jumps propagate through the vertical integration and spherical harmonic analysis, affecting the resulting AOD1B products and probably leading to wrong trend estimation from Level-2 gravity models in time spans that include the two jumps.

In order to overcome this problem, we introduce an a-posteriori correction for Level-2 monthly average coefficients. Since we consider only continental regions, only the monthly mean of the 6-h atmospheric AOD1B coefficients (GAA Level-2 product) and of the combined atmosphere and ocean coefficients (GAC Level-2 product) have to be corrected. The correction will be the same for both of them since they include the same atmospheric part; hence only one product per jump is provided. To this end, we computed two additional Level-2 products called GAE and GAF: GAE is to be used for monthly gravity field determination between 2006 February (included) and 2010 January (included); GAF is to be used after 2010 February (included). They have been calculated as follows:

(1) First we generated new atmospheric coefficients based on ECMWF ERA-Interim reanalysis for the following points in time: $t1^*$, $t1$, $t2^*$ and $t2$; we assumed that these new atmospheric gravity variations represent the true (unbiased) 6 h 'atm' differences. Note that, consistent to the standard procedure using analysis data, for the ERA-Interim products a corresponding mean field based on ERA-Interim data for the years 2001 and 2002 had to be calculated and removed.

(2) Then we calculated the 6-hour variations at *t*1 and at *t*2 of atmospheric coefficients based on operational data (Fig. 3) and on ERA-Interim data (Fig. 4).

(3) Finally we generated GAE and GAF as the difference between the two sets of coefficients (ERA-Interim minus operational) (Fig. 5). GAF have to include both *t*1 and *t*2 variations since the jump at *t*1 superimposes the jump at *t*2 after *t*1.

Fig. 3 shows 6-h atmospheric gravity variations expressed in EWH at *t*1 (left) and *t*2 (right) derived from operational ECMWF data. Besides realistic signatures of surface pressure variation one can note spurious artefacts in form of negative (blue) and positive (red) spots over land. Fig. 4 shows the corresponding results based on ERA-Interim. Patterns are smoother and previous artefacts disappear at both jump events. The exact locations affected by the biases are highlighted in Fig. 5 by subtracting Fig. 4 from Fig. 3. These differences correspond to GAE/GAF in terms of EWH and, as expected, are highly correlated to the estimated bias in terms of hectopascals surface pressure (Fig. 2). More details are described in the last update of the AOD1B Product Description Document for Product Release 05 (Flechtner *et al.* 2014).

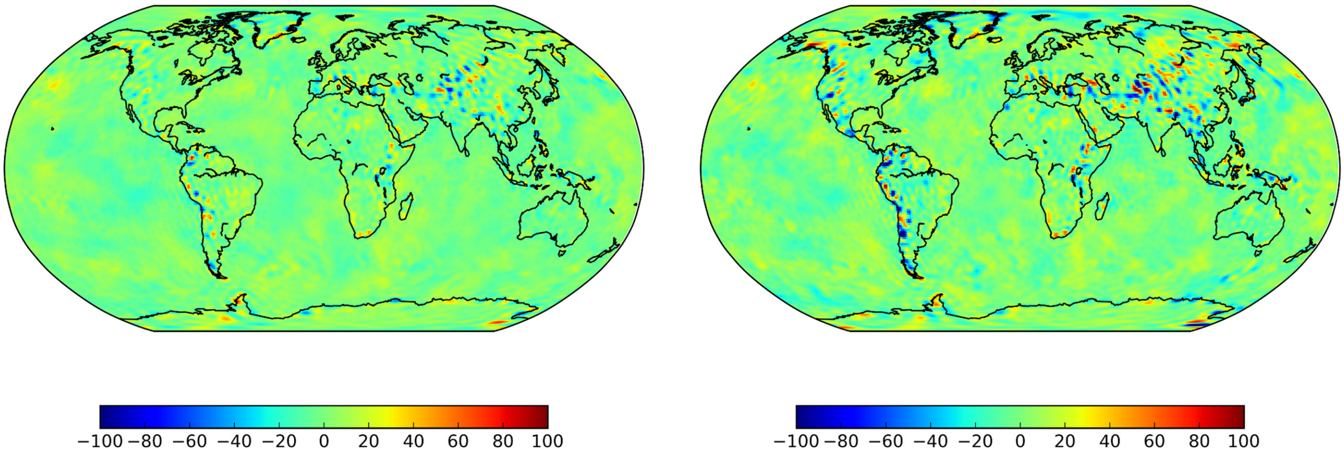

Figure 5. GAE (left) and GAF (right) correction coefficients in millimetre EWH show the biased locations.

3 IMPACT ON GRACE GRAVITY FIELD DETERMINATION

The two new Level-2 products were delivered to the GRACE SDS in terms of technical notes TN08 and TN09 in 2014 April (available at the GRACE archives at both GFZ and JPL). They have to be applied during the spherical harmonic synthesis in order to generate corrected monthly GSM grids for land applications. It is commonly accepted that the processing of GRACE solutions requires the introduction of filtering techniques in order to improve the signal-to-noise ratio. The typical noise for GRACE has a random component that increases with the spectral degree of the spherical harmonic representation (SHR) and a systematic component that causes the so-called 'stripes', which are errors correlated with specific spectral orders of the SHR (Wahr *et al.* 2006). The widely used filter tools for GRACE solutions are of two types: isotropic (e.g. Gaussian smoothing) or anisotropic [e.g. Swenson and Wahr filter (2006), DDK (Kusche *et al.* 2009)]. The selected filter (DDK2 in the following) has to be applied during the spherical harmonic synthesis. A procedure to *a posteriori* correct the RL05 GSM products using GAE and GAF would look like:

$$(\mathrm{GSM}(t) - \mathrm{GAE}(t))^{\mathrm{filtered}}, \text{ for } t \text{ between 2006 February and 2010 January} \tag{1}$$

$$(\mathrm{GSM}(t) - \mathrm{GAF}(t))^{\mathrm{filtered}}, \text{ for } t \text{ after 2010 February.} \tag{2}$$

The difference between the corrected GSM and the original one is equal to the filtered GAE/GAF (Fig. 6):

$$\mathrm{GSM}(t)^{\mathrm{filtered}} - (\mathrm{GSM}(t) - \mathrm{GAE}(t))^{\mathrm{filtered}} = (\mathrm{GAE}(t))^{\mathrm{filtered}} \tag{3}$$

$$\mathrm{GSM}(t)^{\mathrm{filtered}} - (\mathrm{GSM}(t) - \mathrm{GAF}(t))^{\mathrm{filtered}} = (\mathrm{GAF}(t))^{\mathrm{filtered}}. \tag{4}$$

If we want to retrieve the full gravity field signal, including oceanic and atmospheric variations (GSM + GAC), we have to correct both components by means of GAE/GAF:

$$(\mathrm{GSM}(t) - \mathrm{GAE}(t))^{\mathrm{filtered}} + \mathrm{GAC}(t) + \mathrm{GAE}(t) \tag{5}$$

$$(\mathrm{GSM}(t) - \mathrm{GAE}(t))^{\mathrm{filtered}} + \mathrm{GAC}(t) + \mathrm{GAF}(t). \tag{6}$$

In this case the difference between corrected and original GSM is equal to the difference between the unfiltered GAE/GAF (Fig. 5) and filtered GAE/GAF (Fig. 6) and is visualized in Fig. 7.

$$\mathrm{GSM}(t)^{\mathrm{filtered}} + \mathrm{GAC}(t) - (\mathrm{GSM}(t) - \mathrm{GAE}(t))^{\mathrm{filtered}} + \mathrm{GAC}(t) + \mathrm{GAE}(t) = (\mathrm{GAE}(t))^{\mathrm{filtered}} - \mathrm{GAE}(t) \tag{7}$$

$$\mathrm{GSM}(t)^{\mathrm{filtered}} + \mathrm{GAC}(t) - (\mathrm{GSM}(t) - \mathrm{GAF}(t))^{\mathrm{filtered}} + \mathrm{GAC}(t) + \mathrm{GAF}(t) = (\mathrm{GAF}(t))^{\mathrm{filtered}} - \mathrm{GAF}(t). \tag{8}$$

Table 1 shows that filtered GAE and GAF values for the GSM only case present ranges of ∼37 and ∼53 mm EWH respectively, while the GSM with restored atmosphere and ocean case exhibit larger and more localized values (mostly over steep topography). The ranges are of about ∼167 and ∼257 mm EWH, respectively. The GAF correction has a larger impact because both jumps add up after 2010 February.

In order to verify whether the proposed intermediate solution (a-posteriori correction of Level-2 gravity field products by GAE/GAF) is a good approximation of the accurate (a-priori) procedure (corrected AOD1B used in POD), we calculated the difference of the two methods for 2010 January and February (Table 1). First, we corrected 6-h AOD1B by means of GAE/GAF; then we applied the corrected AOD1B during daily GRACE POD and we generated bias-free Level-2 GSM monthly solutions; finally, we compared them with the corresponding a-posteriori corrected GSM solutions. The global differences present considerable low mean (−0.01 mm EWH for both months) and standard deviation (1.1 mm EWH for January and 0.7 mm EWH for February). We also note a slightly worse performance in January, probably due to the fact that the jump occurs on the 26th day and GAE ignores the last four days of the month. Nevertheless, we conclude that the error, also for the minimum and maximum values, introduced by the proposed provisional solution is negligible w.r.t. the current GRACE error level (see Table 1).

4 IMPACT ON ATMOSPHERIC C_{00} COEFFICIENT

Even if the degrees 0 and 1 spherical harmonic coefficients of the AOD1B products are provided to the user, they are usually fixed to zero (as for all the background models) before being applied in the determination of GRACE products. However, the degree 0 spherical harmonic coefficient C_{00} of the atmospheric potential field can be analysed in order to estimate the total mass of the atmosphere and its

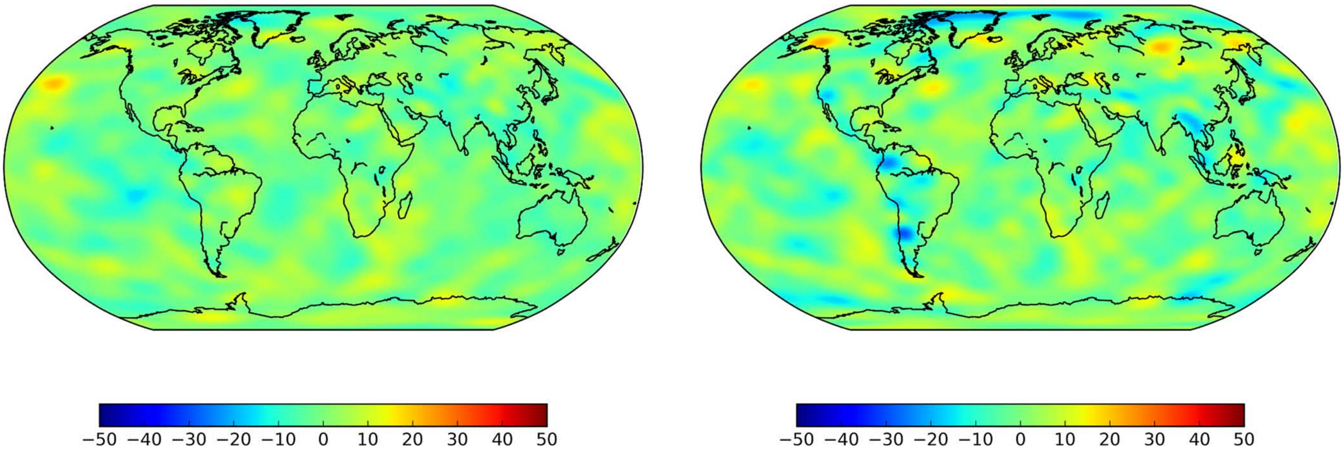

Figure 6. DDK2 filtered difference between corrected and original GSM in millimetre EWH at *t*1 (left) and *t*2 (right).

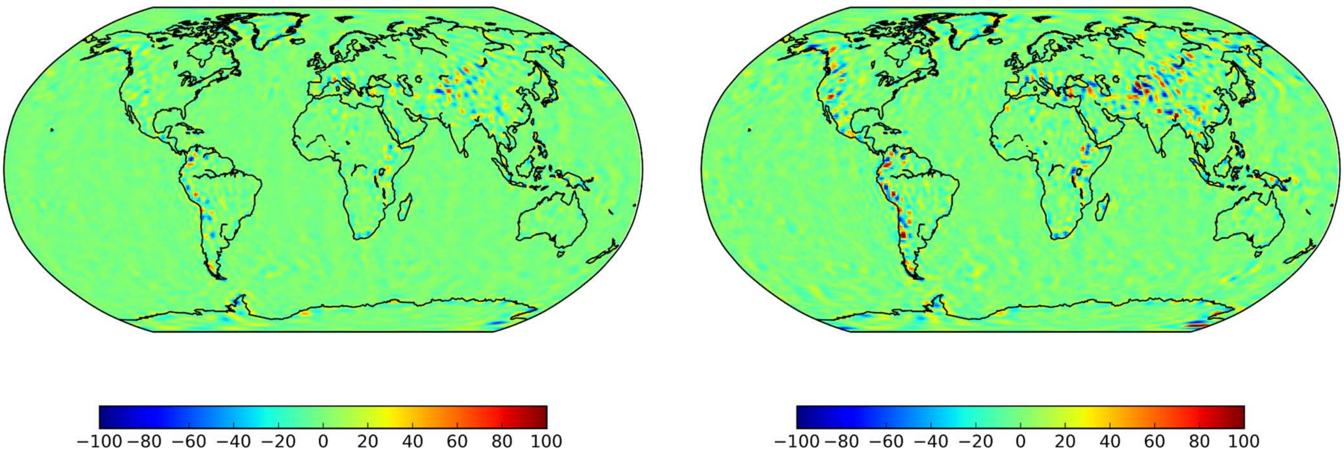

Figure 7. DDK2 filtered difference between corrected and original GSM with restored ocean and atmosphere (GAC) in millimetre EWH at *t*1 (left) and *t*2 (right).

variations. Gruber *et al.* (2009) observed jumps in the C_{00} time series for the period 1998–2006, also due to changes in the operational model of ECMWF. For this reason, they estimated a regression line that excludes the jumps before performing linear fitting for trend determination. In our case, we can apply the GAE/GAF correction including C_{00} and estimate the new trends. Its 6-h variations in terms of millimetre geoid height variability are represented in Fig. 8 for the years 2001 until 2014. The blue line represents C_{00} derived from the operational analysis and the green one the corrected C_{00} by means of the GAE/GAF products. A clear yearly signal is visible in both solutions. The two time series start differing in 2006 January because of the GAE correction and this digression becomes stronger after 2010 January because of the additional GAF effect. Overall, the applied corrections reduce the linear trend from -0.05 mm yr^{-1} of the original solution to -0.02 mm yr^{-1} of the corrected one.

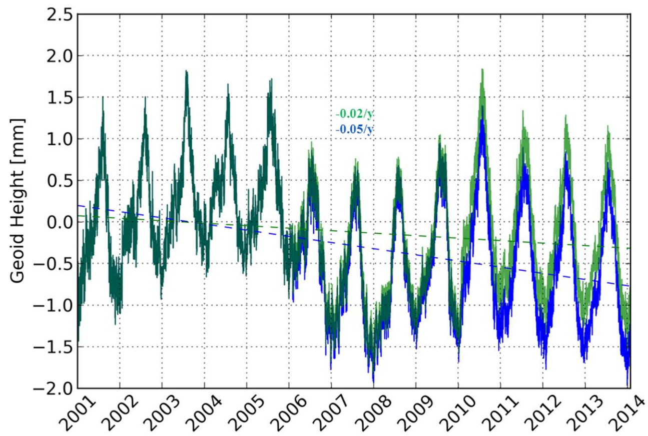

Figure 8. C_{00} spherical harmonic 6-h time series in terms of millimetre geoid height variability for the original 'atm' variability in blue and for the corrected in green. They start differ from 2006, as expected. The corresponding linear trends for the whole time span (indicated by the broken lines) are in both cases negative but stronger for the standard solution.

5 IMPACT ON ICE MASS BALANCE

We also calculated the effect of the GAE/GAF correction on the Antarctic and Greenland ice sheet mass balance for individual drainage basins and for Antarctica and Greenland as a whole. We apply the regional integration approach (Horwath & Dietrich 2009) with an integration kernel that extends into the ocean area to avoid down-weighting signals at the ice sheet margins. We apply the GAE/GAF products without discriminating between ocean and land signals, because such discrimination is difficult based on the spatial resolution allowed by the expansion up to degree 100. It is worth noting that the results are sensitive to the details of the definition of the integration kernel at the ice sheet margins because this is where the GAE/GAF amplitudes are largest. Over

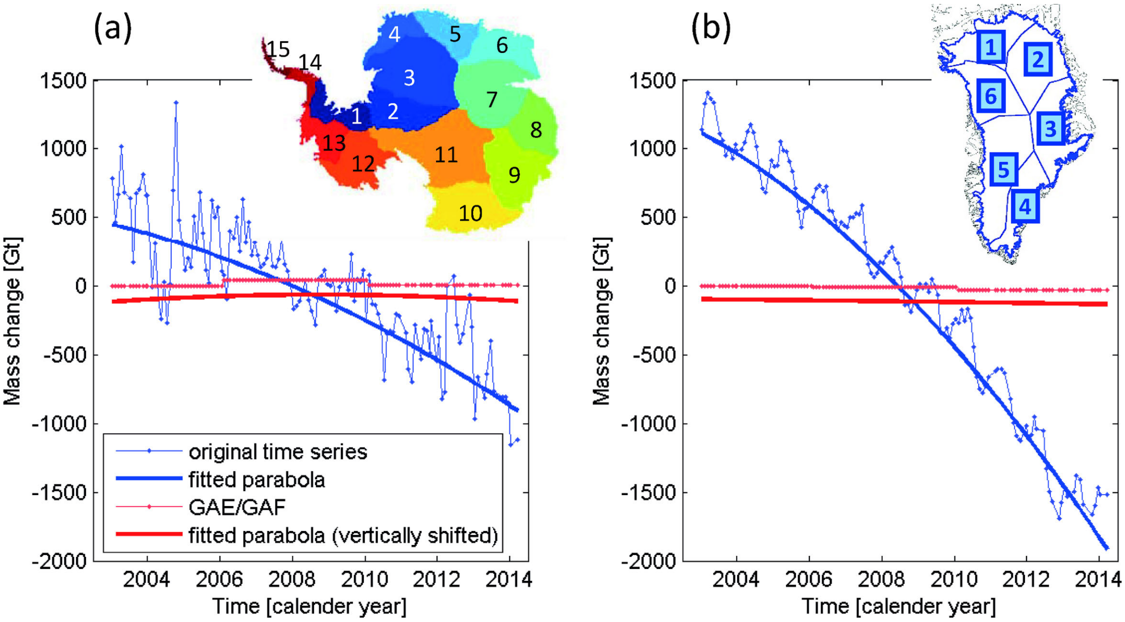

Figure 9. GRACE-based mass changes for the ice sheets of (a) Antarctica and (b) Greenland and the impact of the GAE/GAF correction. Blue: mass changes without GAE/GAF correction. Thick line shows fitted linear + quadratic function. Red: effect of GAE/GAF fields. These curves must be subtracted from the blue curves to obtain corrected results. Thick line shows the fitted linear + quadratic function, shifted vertically for better legibility. Map insets show sub-basins referred to in Table 2.

Antarctica, the effect appears to be small compared to the prevailing ice mass signals and to the noise in the time series. The effect on the linear trend for 2003 January to 2014 March is on the order of ±0.7 Gt yr^{-1} for the entire Antarctica as well as for the individual basins, while the actual ice mass trend is on the order of 120–10 Gt yr^{-1} (Fig. 9a). The proposed correction will be hence significant for more detailed studies, in particular for small basins and specific time intervals. Applying the GAE and GAF corrections will also impact the quadratic term of adjusted mass change time series which represents acceleration of ice mass loss and which is a matter of scientific discussion (Velicogna 2009; Wouters *et al.* 2013). If we apply the GAE/GAF correction then the mass loss over the whole of Antarctica is accelerating 3.2 Gt yr^{-1} yr^{-1} less than without applying this correction. Previous studies as well as our study have estimated this acceleration of mass change on the order of −10 Gt yr^{-1} yr^{-1}, but with large scatter and large uncertainties (Williams *et al.* 2014).

Over Greenland, accounting for the GAE/GAF correction would make the trend about 3.3 Gt yr^{-1} less negative. Instead of −268.3 Gt yr^{-1}, we now get −265 Gt yr^{-1} from the GFZ RL05a time series between 2003 January and 2014 March (Fig. 9b). Again, the relative effect is more considerable for some single basins (Table 2). For example, for northeast Greenland (Basin 2) the ice mass trend without the correction is about −7.8 Gt yr^{-1}, and with the correction it is about −6.5 Gt yr^{-1}.

6 CONCLUSIONS AND DISCUSSION

Within this paper we present a correction method for inconsistencies in the atmospheric part of the AOD1B product which are caused by discontinuities in surface pressure and surface geopotential time series extracted from the ECMWF operational archive. These inconsistencies contaminate the GRACE gravity field solutions as well as many applications derived from these products (e.g. ice mass loss analysis). Since 2001 two jumps are visible: the first in 2006 January and the second in 2010 January. The GAE/GAF correction coefficients have been estimated at these two time points comparing the operational atmospheric input data with the more stable reanalysis ones. They have to be used as an a-posteriori correction for the already distributed Level-2 RL05 GRACE products (GSM, GAA and GAC) and are applicable for continental regions only. We showed that the error by this intermediate solution compared to a more rigorous approach (correction introduced at AOD1B-level during POD) is negligible w.r.t. the GRACE sensitivity. We also estimated the impact of these inconsistencies on the gravity field determination by applying a DDK2 filter, which reaches extreme values of ∼53 mm EWH for the case of gravity with reduced atmosphere and ocean (GSM) and of ∼256 mm EWH for the case of gravity with recovered atmosphere and ocean (GSM + GAC or GAA). In terms of atmospheric mass variations, represented by the degree 0 spherical harmonic AOD1B coefficient, we noted a less negative trend after the application of this correction. The impact on ice mass balance was also analysed and found significant for the acceleration term of the mass loss over Antarctica, estimated to be 3.2 Gt yr^{-1} yr^{-1} less than without the correction (about a third of the total signal). The reason we chose for this study ERA-Interim data is that this data set is more homogeneous and stable in time and therefore more appropriate for long-term analysis (e.g. trend analysis) (Dee *et al.* 2011). However, ERA-Interim is not suitable for the operational GRACE de-aliasing products, since re-analyses are typically delivered from ECMWF with ∼3 months delay. Additionally, the re-analysis has a lower horizontal and vertical resolution of T255 (∼80 km grid spacing) and 60 vertical levels in comparison with the current operational T1279 (∼15.6 km grid spacing) and 137 levels. Moreover, extracting the inputs from two different archives (operational analysis and re-analysis) causes the proposed correction to contain not only the bias that we want to define, but also model differences. Therefore, for future estimation of new jumps, we will avoid introducing the ERA-Interim data and will compare data of same model

Table 2. Ice mass trends and accelerations for ice sheets of Antarctica and Greenland and their sub-basins (see fig. 10 for basin definitions) prior to the correction (columns 2 and 3), and the trends and accelerations inherent to the corrections (columns 4 and 5). Calculations based on GFZ RL05a monthly solutions in the interval 2003 January to 2014 March.

	Trend without GAE/GAF [Gt yr^{-1}]	Acceleration without GAE/GAF [Gt yr^{-1} yr^{-1}]	Trend of GAE/GAF [Gt yr^{-1}]	Acceleration of GAE/GAF [Gt yr^{-1} yr^{-1}]
Entire Antarctica	−120.0	−10.1	0.7	−3.2
Basin 1	−2.6	−4.3	−0.1	−0.2
Basin 2	−0.7	−1.1	0.0	0.1
Basin 3	21.3	0.9	0.6	−0.5
Basin 4	20.3	4.4	0.3	0.1
Basin 5	15.7	5.4	0.0	−0.1
Basin 6	25.9	4.0	−0.4	−0.1
Basin 7	7.3	0.1	0.5	−0.3
Basin 8	5.7	1.6	1.1	−0.6
Basin 9	−11.6	−3.7	−1.0	−0.4
Basin 10	−17.3	3.5	−1.1	−0.2
Basin 12	−2.3	2.4	0.6	−0.4
Basin 11	−37.6	−4.8	0.2	0.2
Basin 12	107.8	−15.0	−0.4	−0.5
Basin 13	−11.8	−4.9	−0.5	0.0
Basin 14	−24.6	1.3	0.8	−0.2
Basin 15	−2.6	−4.3	−0.1	−0.2
Entire Greenland	−268.3	−22.7	−3.3	−0.2
Basin 1	−37.7	−4.3	−1.4	0.0
Basin 2	−7.8	−1.3	−1.1	−0.0
Basin 3	−47.9	0.2	−0.1	−0.1
Basin 4	−55.0	−0.6	0.1	−0.1
Basin 5	−77.4	−13.9	−0.2	−0.1
Basin 6	−42.6	−2.8	−0.6	0.1

type, that is, the operational analyses. This will be possible because at every processing change, the new operational data are made available by ECMWF for test purposes together with the old ones for a limited time period (few days). We will be able to estimate the new correction thus by comparing the nominal atmospheric coefficients, based on the old operational analysis data, with new coefficients based on the new data from the updated operational archive, without adding any latency to the delivery time of the AOD1B products. Moreover, we will introduce and apply a more rigorous a-priori approach which will consist of (1) extending the GAE/GAF to the ocean component by considering additional OMCT experiments in order to verify the inverse-barometrically adjustment, (2) correcting the affected 6-h AOD1B coefficients, (3) applying these corrected Level-1 background models during daily GRACE POD and (4) consequently during the monthly Level-2 GSM determination. In conclusion, the proposed method is adequate for gravity mission analysis as well as for POD of missions that use the same background model (e.g. altimetry missions). Moreover, the impact should not be underestimated, since we expect Next Generation Gravity Missions to show higher sensitivity to mass variations and consequently to such effects.

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