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Antarctica seasonal mass variations detected by GRACE

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Abstract

The newly available GRGS-EIGEN-GL04-30day solutions computed by the GRGS group in Toulouse are used to study inter- and intra-annual mass variations in Antarctica. The series of gravity coefficients cover the period from July 2002 to March 2005. They are corrected for ocean tides, ocean high frequencies and atmospheric pressure, so the remaining signal mostly comes from ice mass variations and post-glacial rebound. The errors of these fields are estimated to be less than 2.4 cm of water height equivalent, with punctual values of only 0.5 cm. The polar Antarctica zone benefits from a low error level, which compensates for the weak gravity variations. The temporal signal computed over the whole continent shows a clear seasonal cycle, with a maximum of precipitation during winter months and a minimum during summer months. The ratio between winter and summer snow precipitation is also estimated to be 2.75 which accords well with previous studies. The gravity fields are developed to provide suitable information up to 666 km. The study could therefore focus on regional areas. The coastal zones exhibit higher variable signals with stronger snow accumulation rates than the central part, in agreement with climatologic models and *in situ* observations. The peninsula zone has the highest values, with a clear semi-annual component.

Keywords: Antarctica; seasonal variations; GRACE; accumulation rate; inter-annual; gravity

1. Introduction

Antarctica ice sheet is the largest reservoir of ice on Earth. Among the numerous unknowns, two are of prime importance: its mass balance for sea level change and the accumulation rate for ice sheet modelling, climate and balance studies (Van der Veen, 2002).

Measuring precipitation or accumulation rate is very difficult, because of the snow transport due to the strong katabatic wind, because of the strong variability in time and space, and because of the weak values (less than 5 cm over the central part). The recent discovery of the megadune (Frezzotti and Polizzi, 2002) is a good example because it points out the strong impact of redistribution processes on the annual scale variability of accumulation. Moreover, the precipitation is known to be very variable in space and time, so that the scarce *in situ* measurements cannot be easily extrapolated. In addition, modelling still suffers from certain limitations, for instance surface mass balance deduced from modelling for the interior of the continent yields significantly lower values than that provided by *in situ* surface mass balance estimation (Turner et al., 1999).

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The long series of data from the ERS1, ERS2 and Envisat altimeters now allow a first estimate of volume change. However, due to snow densification and to isostatic rebound, the volume fluctuation may not be related to the ice mass change. Moreover, altimetric series are affected by temporal change in the snowpack (Legresy and Remy, 1998) so that the significant errors may occur when deducing the mass balance. It has therefore been recognized that measurements from both altimetry and gravity are needed to retrieve mass balance series correctly. Unfortunately, the series of gravity missions is still too short to be used with altimeters to provide the ice sheet secular trend, all the more so as it has recently been shown that the snow accumulation variability mixed with the snow densification prevents a correct interpretation of both altimetric and space gravimetric missions of less than 10 yrs (Rémy and Parrenin, 2004).

The first gravity missions from space flying over Antarctica in recent years are likely to be a good tool for glaciological studies (Llubes et al., 2003). Now with GRACE, time-varying studies can be performed. In the first place, the study focuses on the interpretation of gravity data over a short time scale. On this time scale, it could be assumed that due to the considerable dynamic inertia, the loss by ice flow is constant, so that gravity variability reflects snow precipitation and melting events. This provided information on when precipitation occurs within the year. In theory, if the loss by ice flow is known, the gain by snow precipitation can be retrieved by this technique. However, due to uncertainty concerning ice flow, only the intra-annual distribution of precipitation can be retrieved with reasonable confidence.

This information is nevertheless very important. First, snow precipitation is a key input for ice sheet modelling and also for mass balance estimation. The horizontal and vertical velocities depend mostly on snow accumulation. For instance, an error of 10% of the mean value has a direct effect on the velocities and leads to a bias of 0.06 mm/yr in terms of sea level rise. Second, its behaviour with respect to climate forcing is needed also for the prediction of future mass balance. Up to now, the relationship between precipitation and temperature has always been deduced from ice core analysis and demonstrated only at the long climatic cycle scale. Over the decadal scale, the current scenario inferring surface balance change versus temperature change is not proved. Thus the knowledge of processes that control precipitation and its temporal variability is one of the unknowns for predicting its future evolution versus climate change. Finally, the knowledge of the temporal distribution of snow events, even without the knowledge of the absolute value, is also needed for a correct explanation of the annual variability of sea level, which is a useful tool to constrain the seasonal water exchange with the main other surface reservoirs (ocean, atmosphere, continents or ice sheets) (Cazenave et al., 2000).

The aim of this paper is to use the GRACE mission, which is at present the most appropriate tool, to provide information about ice mass fluctuations in Antarctica (Tapley et al., 2004). In this paper, the GRGS-EIGEN-GL04-30day fields, developed by the GRGS (OMP, Toulouse), are used to compute temporal variations over a period of 2.5 yr. Because of the short period of observation, the study focused on the seasonal signal and there was no attempt to interpret the tendencies profoundly.

We first present the 86 gravity fields from GRACE and give an error assessment according to their resolution. Then, we explain how gravity maps at several periods can be obtained over Antarctica and how we plot the curve of time variations expressed in water height equivalent. This result provides information about snowfall distribution and we discuss this, proposing also an estimation of the accumulation rate. We confront the seasonal variations of the curve from GRACE observations with other studies, showing a relatively good agreement.

2. Preliminary methodological approach

2.1. The GRGS GRACE solutions

The GRGS-EIGEN-GL04-30day solution is a series of monthly models of the Earth's gravity field produced by the CNES/GRGS group in Toulouse using GRACE data. The twin GRACE satellites, which follow the same, almost polar, track at a distance of 200 km from one another, allow the computation of static and time-variable gravity fields with unprecedented accuracy thanks to the ultra-precise (1 micro-meter) K-band ranging between them.

The GRGS-EIGEN-GL04-30day models are expressed in normalized spherical harmonic coefficients from degree 2 to degree 50. These fields are provided every 10 days and are based on the running average of three 10-day data periods with weights 0.5/1.0/0.5. They are recovered from GRACE GPS and K-band range-rate data and from LAGEOS-1/2 SLR data. To date, 86 models of this type have become available and were used in this study, covering nearly three years, from July 29th, 2002 to March 24th, 2005. They span 95 consecutive 10-day periods, of which only 86 could be finally produced according to criteria of availability or quality of data.

The static gravity field model EIGEN-GL04S is used as a reference to compute the time variations of the gravity field. EIGEN-GL04S is the mean – or static – gravity field associated with the GRGS-EIGEN-GL04-30day solution. It was computed from a subset of 73 10-day data periods covering exactly two years (February 24, 2003 to February 23, 2005) in order to avoid the aliasing of this mean field by seasonal processes.

The following *a priori* gravitational variations were taken into account in processing the data: IERS Convention 2003 Earth body tides, FES2004 ocean tides with ellipsoidal corrections (Lyard et al., submitted for publication), ECMWF atmospheric tides, 3D-ECMWF atmospheric pressure fields every 6 hours and the MOG2D barotropic ocean model (Carrère and Lyard, 2003). The time-variable gravity field models therefore only depart from the static gravity field by the unmodelled effects: hydrology, snow cover, baroclinic oceanic signals, post-glacial rebound and all tectonics events. The uncertainties of those fields include errors in the measurement data, in the processing, lack of coverage in some instances, and possible remaining errors in the FES, MOG2D and ECMWF models.

The time-variable signal that GRACE is looking for is very weak. Above harmonic degree 30 the errors of the monthly fields tend to be greater than the geophysical time-variable signal. This is why, at construction, the monthly solutions were progressively constrained, between degree 20 and 50, towards the static solution EIGEN_GL04S in order to stabilize them. The constraint is approximately 1% at degree 20 and 90% at degree 50. Thus the theoretical spatial resolution of 3.6°, or 400 km, at harmonic degree 50 cannot really be attained. The effective resolution of the GRGS-EIGEN-GL04-30day solution is closer to 6° or 666 km.

2.2. Error assessment of the GRGS GRACE solutions

The evaluation of the error of the GRGS-EIGEN-GL04-30day series is crucial to the present study, since the gravity signal expected over Antarctica is much weaker than over other areas of the world. In Fig. 1 we plot the amplitude spectrum of the variable gravity signal of the GRGS-EIGEN-GL04-30day solution (Stars) in water height equivalent, its uncertainty (Triangles), the cumulated error (Circles) and, for reference, the error curve of the static field EIGEN-GL04S (Squares). From degree 2 to degree 30 the time-variable signal dominates the noise and its power spectrum appears flat, close to 1 cm/dg. Above degree 30, the influence of the constraint towards the mean field operates and both the signal and the error artificially diminish. The overall cumulated error of the GRGS solution is less than 6 mm water height equivalent (w.e.) at 2000 km resolution, 1.5 cm at 1000 km and 3 cm at 666 km.

The curves of Fig. 1 represent the global error estimate of the GRGS solution, averaged over the whole Earth. By using the variance/covariance matrix of the GRGS-EIGEN-GL04-30day series, it is possible to plot the geographical repartition of the error (Fig. 2).

The geographical distribution of the error is zonal, with a maximum at the equator and a minimum at the poles. This is due to the convergence of the satellite tracks towards the poles where the observation density

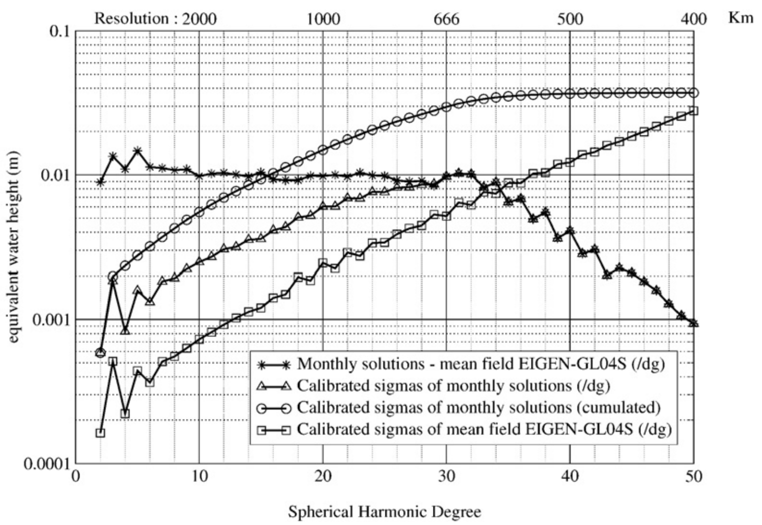

Fig. 1. Error estimate of the GRGS-EIGEN-GL04-30day solution, computed per degree (bottom scale) and corresponding resolution (upper scale). Spectra are expressed in meters of equivalent water height.

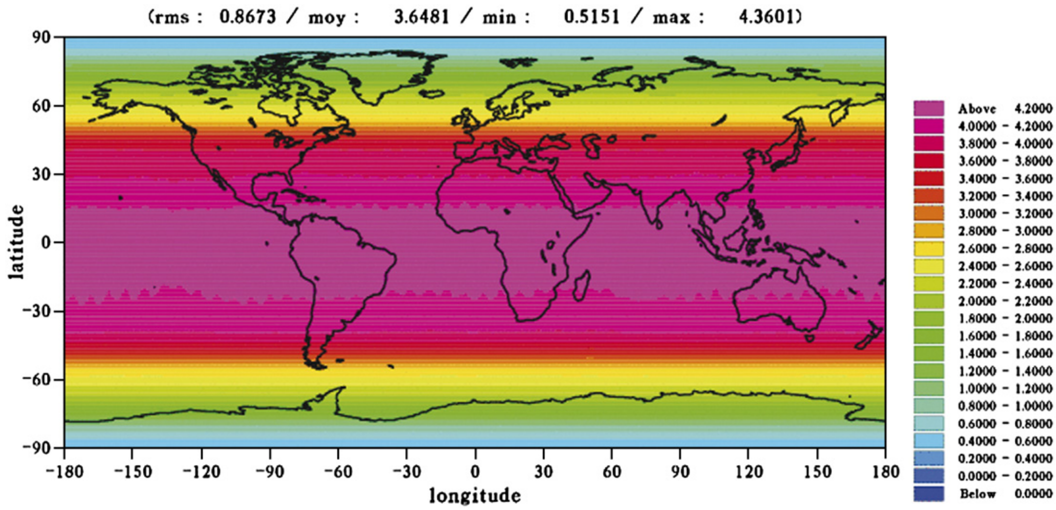

Fig. 2. Geographical distribution of the GRGS-EIGEN-GL04-30day solution error, in cm of equivalent water.

increases in consequence. This is fortunate for the study of Antarctica, where the total error at 666 km resolution is never greater than 2.4 cm w.e. and can be as small as 0.5 cm. The average error ratio between North Africa for instance and most of Antarctica is of the order of 2.8.

An "external" error check was performed to cross-check the above "internal" error assessment. It consists in the delimitation of a "null-zone" where a null temporal gravity signal was expected. The variations of the models in this zone are then considered as error, and can be used to estimate the error in Antarctica for each GRACE solution. The African desert is known to have no seasonal variations and is therefore a good area to make this test. The region between longitudes 5°W and 15°E, and latitudes 20°N and 28°N was selected. The 86 GRACE maps over this specific area were computed and the RMS value of each map was extracted. The result is mostly around 3 to 5 cm w.e. (maps do not share the same error budget). Following the 2.8 ratio between the errors in North Africa and Antarctica obtained from the covariance matrix of Fig. 2, this ratio was applied to the RMS of the African area, obtaining the estimated error in Antarctica for each of the 86 GRACE solutions.

The study defined several zones in Antarctica over which mean values of the gravity signal were computed. This is equivalent to a change of resolution of the analysis. Thus the final errors take into account the surface of these zones with respect to the 666 km resolution of the gravity fields. The error values are very small for the continent as a whole, between 1.7 and 5 mm w.e. (Fig. 3). Higher values were reached for the sub-areas, with a maximum of 16 mm in the coastal basins (see further description and Fig. 7).

2.3. Maps of mass variations

Gravity coefficients up to degree 50 were used to compute maps of geoid height, as seen by GRACE. The values are converted in water equivalent, named $\Delta\sigma_w$,

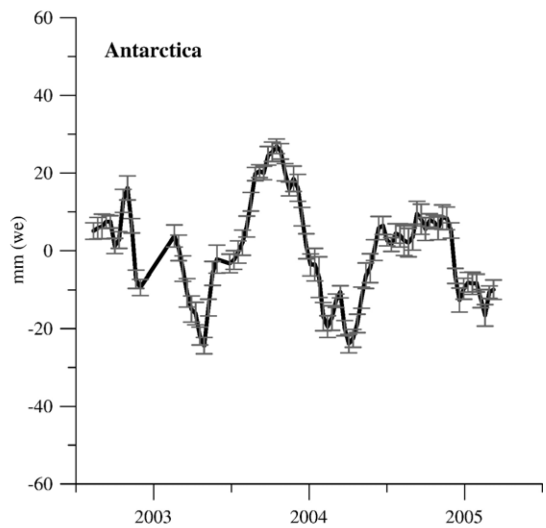

Fig. 3. GRACE solutions computed over Antarctica with coefficients from degree 3 to 50 of the 86 GRGS-EIGEN-GL04-30day fields. They cover the period from July 2002 to March 2005. The mean field is removed. Results are plotted in mm of equivalent water height.

using a formula similar to the one given by Wahr (Wahr et al., 1998):

$$\Delta\sigma_w(\theta,\lambda) = \frac{g}{4\pi G\rho_w}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l} \times (C_{\mathrm{lm}}\cos(m\lambda)+S_{\mathrm{lm}}\sin(m\lambda))\,\tilde{P}_{\mathrm{lm}}(\cos(\theta)) \quad (1)$$

where g is the surface gravity (=9.8 m/s^2), ρ_{w} is the density of water (=1000 kg/m^3), λ and θ are east longitude and colatitude. C_{lm} and S_{lm} are dimensionless coefficients of the geoid spherical harmonics decomposition, and $\tilde{P}_{\mathrm{lm}}$ are normalized associated Legendre functions.

We evaluated $\Delta\sigma_w(\theta,\lambda)$ on a 1 × 1 grid covering the whole of Antarctica, or over a sub-zone of the continent. To obtain a mean representative solution, we simply summed all those points. It is not necessary to apply any smooth averaging kernel or Gaussian filtering function during the computation because the GRGS team solution takes special care to diminish artifacts coming from the spherical harmonic decomposition. In order to stabilize the fluctuations at higher degree coefficients a constraint toward the mean field is applied which is progressive from degree 20 and mainly effective from degree 30 and up. Above this degree, there is no difference with the mean static field. The purpose of this work was to study temporal variations, so it was better to subtract a reference value from the value measured for each map, usually chosen to be the "static" geoid.

In this paper, we present two results. The first one is a GRACE-only solution starting at degree 3 and involving the recombination of harmonic coefficients up to degree 50. This result is shown in Fig. 3. We compute a second result using degree 2 and degree 1 coefficients to obtain the most complete and realistic curve for the time variations on a seasonal scale. For degree 2, we need to use Lageos data jointly with Grace data to stabilize the solution and diminish the error level. The study of degree 1 is trickier because this degree describes translations of the centre of masses that cannot be seen by GRACE observations. Then we only use Lageos observations to obtain coefficients of degree 1 and we correct them for oceanic and atmospheric effects (using MOG2D oceanic model and ECMWF pressure fields respectively). Degree 1 and degree 2 can reach very high amplitude for seasonal variations, almost the signal from degree 3 to 50. They are plotted in Fig. 4a and b. It is very difficult to give an estimation of the error for these two degrees, but it is certainly higher than the error plotted in Fig. 3. Fig. 5 shows the total signal over Antarctica, computed with degrees 1 to 50.

As oceanic and atmospheric effects have been removed from GRACE solutions, the maps can be directly interpreted in terms of ice mass variations. Although these corrections are made using the most accurate fields, a supplementary noise can be added to the observations, especially from the atmospheric effect which sometimes reaches amplitudes of the same order of the observed gravimetric signal. We used 3D-ECMWF fields to take account of the atmosphere. They are the most accurate fields actually available because they assimilate a lot of

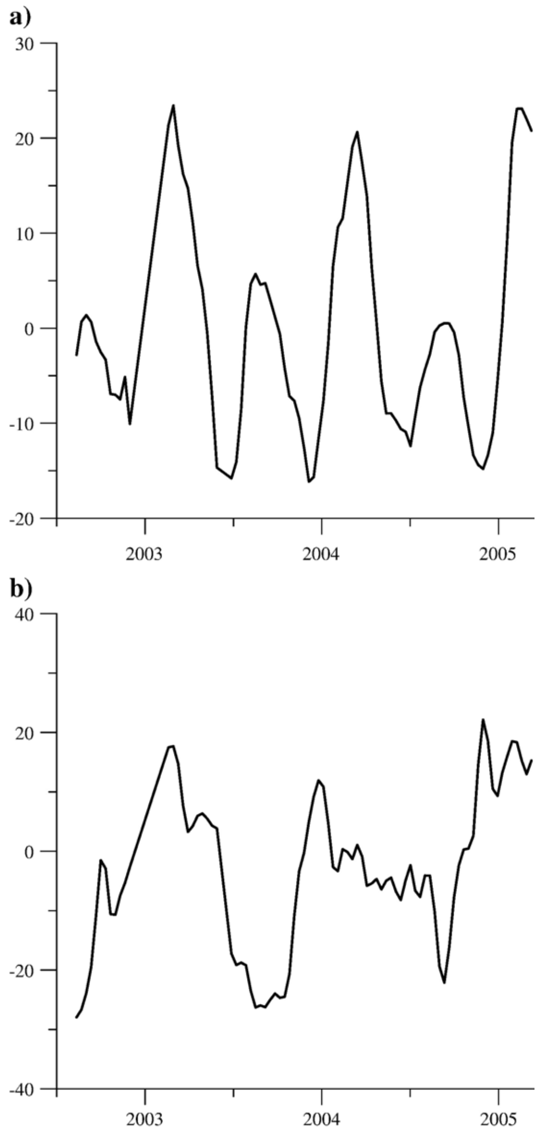

Fig. 4. (a) Degree 1 computed over Antarctica from Lageos data for the period corresponding to GRACE solutions. The curve is corrected for oceanic effects (MOD2D model) and atmospheric effects (ECMWF). (b) Degree 2 calculated with GRACE and Lageos data, over the same area. Units are mm of equivalent water height.

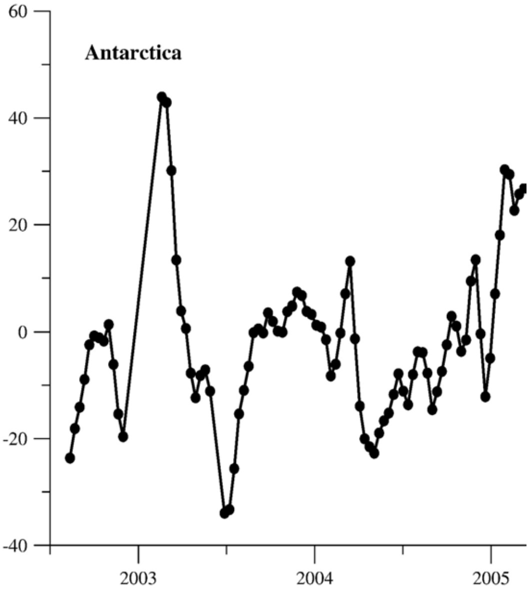

Fig. 5. Mass variations over Antarctica computed from degree 1 to 50, expressed in mm of equivalent water height.

satellite data. It has been shown that data from space are as efficient as ground data for atmospheric fields, with the advantage that they cover the totality of the planet in a dense network, compensating for the lack of data in Antarctica. Then, errors in the southern hemisphere are equivalent to errors in the northern hemisphere. A comparison between ECMWF and Automatic Weather Station showed RMS differences smaller than 2 hPa in the interior of Antarctica, and values up to 4 hPa along the coast, which is equivalent to a water height of respectively 2 cm and 4 cm.

3. Ice flux distribution in Antarctica

3.1. How GRACE can provide information about ice variations

The equation which describes the variations in the height of ice is:

$$\frac{\partial h}{\partial t} = -\frac{\partial Eu}{\partial x} + b \qquad (2a)$$

where h is the height of ice, E is the ice thickness, u is the velocity, x is the flow direction, and b is the accumulation rate. The variations recorded by GRACE are the sum of these two opposite terms, ice loss and snow accumulation. However, the GRACE observations give us the relative change of mass during a time ∂t. We cannot assume that during the year, no accumulation rate occurs within ∂t. We thus add $b_{\min}$ which represents the minimal value of accumulation over ∂t time during the time between observations.

$$\frac{\partial h}{\partial t} = -\left(\frac{\partial Eu}{\partial x} - b_{\min}\right) + b - b_{\min}. \qquad (2b)$$

For instance, if the snow accumulation rate, like the loss by flow, was continuous over time, the signal should be constantly zero. This quantity is probably very weak inside the continent, but it is almost completely unknown near the coasts. This is the difficulty in interpreting the temporal signal provided by GRACE. Moreover, the zone of maximum accumulation is also the zone with maximum ice losses.

3.2. The continental scale

The temporal series start in July 2002 and end in March 2005. Compared to other regions, variation over Antarctica is low; for instance it can reach an amplitude of 30 cm w.e. in the Amazonian basin (Ramillien et al., 2005), and it is of 16 cm w.e. peak-to-peak over Greenland (Velicogna et al., 2005). Despite this weak amplitude, the Antarctica signal provides relevant information. It should be remembered that polar regions benefit from a better signal/noise ratio.

In Fig. 3 we plot the variations from degree 3 to 50 of GRACE coefficients. Each point of the figure can be considered as an instantaneous mass balance. The quantity of mass added – or subtracted – between two successive observations is given by the difference between two points. The computation of the derivative was interpreted as a “mass variation rate”. However, the curve in Fig. 3 shows a clear annual cycle, more or less regular over the plotted period, meaning that at a global scale the accumulation rate occurs at preferential seasons. This is in agreement with previous studies by Bromwich (Bromwich et al., 1995) or Cullather et al. (Cullather et al., 1998). Fitting a cosine curve with annual frequency gives an amplitude of 15 mm. This adjustment is lower than the maximum in 2003, but higher than the maximum in 2004. It points out the modulation of the snowfalls from one year to the next. During 2004, the snow accumulation does not reach the value observed in 2003. But precipitations in 2004 are strong and mostly constant for a long period, and the mean accumulation rate for this year is a little higher than the one for 2003. On Fig. 3, the maximum mass occurs during October and the minimum during April.

We complete the signal for degrees 1 (Fig. 4a) and 2 (Fig. 4b), using Lageos data. Intrinsically, the new curve on Fig. 5 does not change very much compared to the previous one on Fig. 3. The values are shifted by 60 days, and so the minimum occurs at the end of June and the maximum during November. This is the observation for year 2003. In 2004, the snowing period starts earlier – at the beginning of May – and lasts till January 2005. The differences from one year to another reflect the natural climatic fluctuations, with irregular snowfalls events during the time. However, a period of snowy months clearly appears during austral winter, sometimes extended over austral spring. This result is in agreement with studies of atmospheric precipitations (see for instance Cullather et al., 1998; Oshima and Yamazaki, 2006).

Clearly, seasonal variations and uncertainties are still too strong to allow the study of a long-term trend in Antarctica.

3.3. Short scale distribution of mass

Previous studies used GRACE successfully for smaller scale areas, such as Alaska (Tamisiea et al., 2005). The whole Antarctica continent covers a disk of about 5600 km radius. It has been stated that GRACE observed gravity variations with a spatial resolution of 666 km. It was therefore decided to separate the zone of study into several smaller areas. Climatology and morphology assumptions were used to define five "basins" whose size is adapted to the resolution limit. The first zone covers the peninsula plus an adjacent area. Three coastal zones were delimited between longitudes −20°E and 180°E. A fifth sub-area covers the centre of

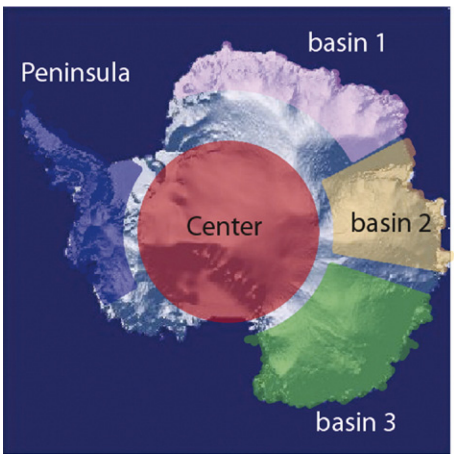

Fig. 6. Delimitation of the five sub-areas selected in Antarctica to study mass variations at a smaller scale (see text): the peninsula zone, three coastal areas (Basins 1, 2 and 3) and the central part of the continent.

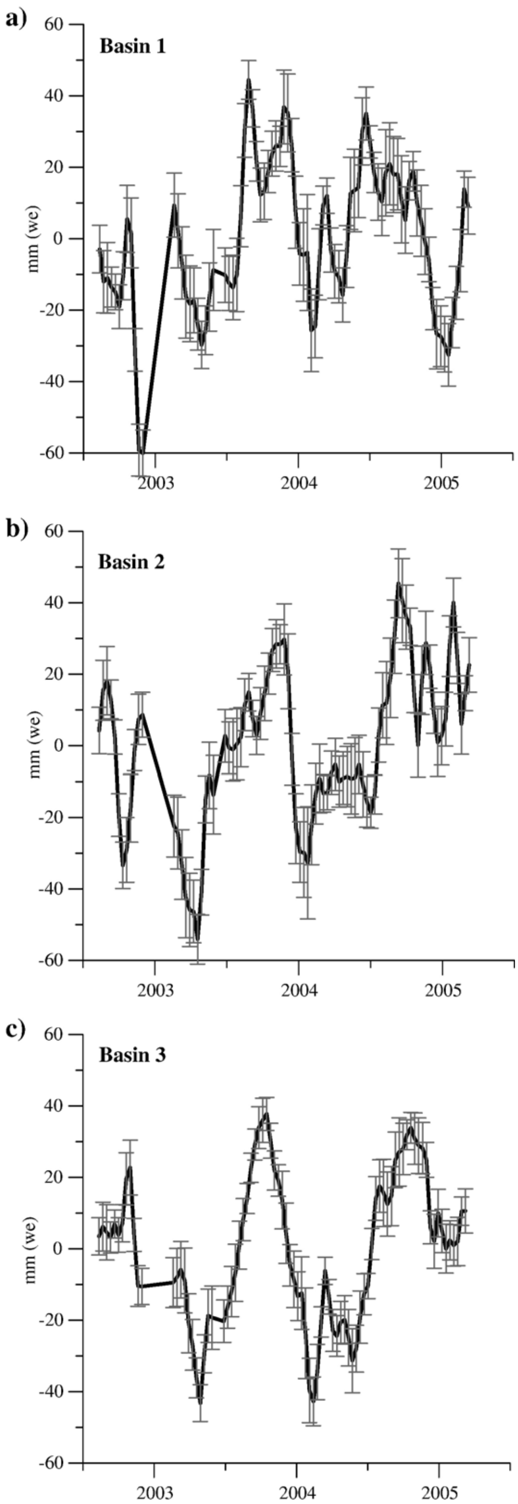

Fig. 7. Mass variations in mm of equivalent water height computed for the three coastal sub-areas. Basin 1 (a), Basin 2 (b), and Basin 3 (c) are plotted respectively.

the continent, from latitudes above −80° to South Pole. Fig. 6 shows the boundaries of these five zones.

The three coastal basins have stronger varying values than those for Antarctica as a whole. They are plotted in Fig. 7a, b and c. The variations are up to twice as large as those for Fig. 5. This is in agreement with the models and meteorological studies which predict most abundant snow falls along the coasts (Turner et al., 1999; Van Lipzig et al., 2002). The damp air coming from the ocean condenses into snow when arriving over the continent. It rarely reaches the high Antarctica plateau. In Fig. 7, the annual period of the signal is sometimes less evident because variations are mixed with other seasonal periods. As Basin 3 shows the most regular curve, it is fitted to a cosine with annual frequency plus a cosine with semi-annual frequency. The adjusted curves have respective amplitudes of 24 and 10 mm, and the semi-annual one is shifted by 3 months with respect to the annual one — its maximum occurs in June. Due to the small surface of these zones, the estimated errors are strong and limit the interpretation. The second basin is the only one to present a positive trend, pointing out a possible ice accumulation that must be confirmed by further studies.

The central zone is not plotted because it is very similar to the curve in Fig. 5. It is surprising because a very weak signal could have been expected in the centre of the continent. The mass variations for the zone outside the central area were therefore computed, which confirmed that each one is in phase with the Antarctica curve and has comparable amplitudes.

Finally, the strongest values are reached in the peninsula. On Fig. 8, the curve varies between 107 and −120 mm w.e. There is a decreasing trend which confirms the permanent loss of ice mass in this zone, located at the northernmost part of the continent. After correcting the values for this trend, variations are apparent between −80 to 60 mm. The signal is significantly semi-annual, particularly during year 2004.

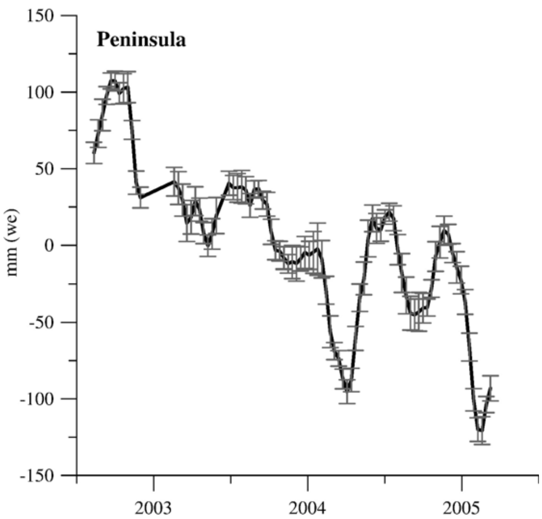

Fig. 8. Idem as previous figure but for the peninsula area.

4. Discussion

According to Vaughan et al. (Vaughan et al., 1999), the net surface mass balance over the grounded ice sheet is 166 mm/yr. The hypothesis was made that Antarctica is in a balance state, and it was supposed that losses exactly compensate the ice rate accumulation. In the event of a regular ice flow and no other type of losses – no melting, no sublimation, and no erosion – regular losses by flow can be considered to be equal to 166 mm/yr. Precipitations occur during the increasing parts of the curve in Fig. 5, and they are small or negligible during the decreasing periods. In 2003, the difference between the minimum and maximum values is 41 mm w.e. of mass variation, from June to November. If this value is added to the losses by ice flow during the same time, 110 mm of ice accumulation is obtained for this 5-month period. To complete the net mass balance value, 56 mm of ice accumulate during the rest of the year. There is a ratio of 2.75 between the winter and summer periods. This result is very close to the 2.5 ratio estimated by Bromwich (Bromwich et al., 1995) and Cullather (Cullather et al., 1998). However, we see large modulations in 2004. The snow distribution differs a lot during this year, with a snowing season starting very early and lasting at least 8 months. Such a ratio between the winter and the summer periods seems completely inappropriate for 2004. Consequently, we can compute the mean accumulation rate encountered during the snowy periods. We find 22 mm/month in 2003 – coming from the 110 mm of ice accumulation divided by 5 months – and with the same calculus we find 20 mm/month in 2004.

From precipitation data at several stations, Bromwich (Bromwich et al., 1988) reported a dominant seasonal cycle, with a minimum precipitation during austral summer. He also used different meteorological analyses (ECMWF, U.S. National Meteorological Center and Australian Bureau of Meteorology) over the whole continent and reported a maximum precipitation during austral winter. GRACE observations confirm this seasonal cycle. The annual frequency cosine previously fitted on Fig. 3 is of amplitude 15 mm. In terms of sea level, this corresponds to an annual signal of 0.5 mm amplitude (1 mm peak to peak).

In Fig. 5, the decreasing parts of the curve have the same type of slope, comparable to the loss value considered above (166 mm/yr). This suggests that the $b_{\min}$ rate of Eq. (2) is really small, indeed negligible, and that snowfall can be zero for weeks at a time even at the global scale.

Over a 10-day period, a 10 mm maximum of mass variation was found, corresponding to a rate of 360 mm/yr. When the ice flow is taken into account, a value of 526 mm/yr for the maximum accumulation rate over Antarctica is obtained. Such a 10-day period (3% of the year) represents 9% of the total mass balance.

Finally, no clear tendency emerges from these first gravity fields. The peninsula and the second basin are the only ones to show a clear tendency, respectively of −55 mm/yr and +13 mm/yr in good agreement with other studies (Davis et al., 2005). That may indicate a permanent loss of ice rate in the peninsula, and a permanent growth rate in the eastern basin. To interpret these values correctly, one must take into account the Glacial Isostatic Adjustment (GIA) that adds a constant trend in mass variations. Using a model such as ICE-5G for a reference (Peltier, 2004) would give corrected values suitable for ice tendency determination. The accuracy of post-glacial rebound models will not be discussed in this paper because it is dedicated to seasonal signals. A detailed study of GIA is presented in (Ramillien et al., accepted for publication). Another approach would consist in the joint inversion of several types of data to separate each phenomenon (Velicogna and Wahr, 2002). However that may be, the tendencies that could be found are only tendencies for 2.5 yr of observations. GRACE mission will continue. It is anticipated that research will now concentrate on identifying a representative and accurate trend.

5. Conclusion

For the first time, it is possible to use operational mass variation data at a global scale on Antarctica. It remains a challenge because the temporal signal is weaker than in other regions. Luckily, the errors contained in the computed gravity solutions are small enough to provide useful information. The seasonal cycle reported by previous studies (Bromwich et al., 1995; Cullather et al., 1998; Oshima and Yamazaki, 2006) over the whole continent is confirmed. Snow falls mainly between June and November and the minimum precipitations are during austral summer. The year 2003 is a very clear example of a typically annual cycle. Some higher frequency fluctuations also occur and differences between two successive years can be seen.

Small scale studies focused on specific zones are possible as long as the limit resolution of 666 km is respected. The results obtained in such coastal sub-areas show higher variable signals, with higher snow accumulation rates. Errors for small scale studies are higher but they never overrun 16 mm w.e.

GRACE is an efficient tool for providing information on seasonal mass variations, even on the scale of individual basins. Because of the large climatic fluctuations from one year to another, it is still difficult to obtain mean accumulation rates or an estimation of ice losses during the seasonal exchanges between the icecap and other reservoirs. This study is very promising and we wait for longer time series that, combined with altimetric data, will provide complementary information about distribution of snow precipitations.

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