Response to M. An (referee)

General comment

An : « *Gravity observations can offer reliable information about variations in Moho topography, but not absolute thickness values, therefore, absolute thicknesses from seismic studies are often taken as a priori constrains in gravimetric inversion. The constraints used in this manuscript are from global model, CRUST1.0, but it gives little information on Antarctic interior.* »

Yes, gravity data allow us to access crustal thickness variations with respect to an average value, and not absolute thicknesses. This is our unique constraint. We chose a 35 km value based on mean values from seismological models, not only CRUST1.0, and from literature.

Using a mean value during the inversion process has no influence on the resolution of gravimetric results. Our thickness model gives information near the coastlines as well as in the Antarctic interior. Using gravity data from space allows us to benefit from a complete coverage of equal quality, and reveals details about the crustal structure anywhere on the Antarctic continent (except inside the small zone around the south pole where GOCE data are lacking).

An: *"New results (e.g. AN1 model) showed that the crust of Antarctica is very different with those (e.g. CRUST1.0) imagined previously. However, the new results were not considered in the manuscript".*

Our aim is to propose an upgraded model for the crust thickness variations in Antarctica, using the last and most detailed available gravimetric field. It was interesting to confront the result with other models proposed by seismological studies. CRUST1.0 is one of the most famous, but it was built considering some gravimetric data. So, we completed our comparison choosing a model fully independent from gravity data, and only based on seismological data: AN1 is the most recent one. We considered this new result in our study, especially on figure 8 of our paper where differences between all models are presented.

Specific comments

Authors reply to comment (1).

An: "The text in the manuscript about the observations used in An et al. (2015) is that "in Antarctica there are very few seismological observations and the Chinese model is poorly constrained" (page5, lines 11-12). This statement is completely wrong. It is true that there had ever been few seismological observations in Antarctic *before 2007. However, since the IPY (2007–2008), intensive seismological surveys under GAMSEIS and POLENET projects have been conducted in Antarctica. Those observations significantly improved the coverage of seismic observations in Antarctica. As one work of the GAMSEIS project, An et al. (2015) not only used almost all seismological observations before the IPY, but also the observations of GAMSEIS and POLENET. Their model was constrained by the best data coverage on entire Antarctica to date."*

We have changed the text in page 5 lines 13-14 into: "in Antarctica there are very few seismological observations compared to gravity data, for example, in areas of East Antarctica as QML (Queen Maud Land) and AGV (George V land) (see Kanao et al. 2013 figure 1 to see the station distribution or An et al. 2015 figure 4) "

An : "After a comparison with AN1 of An et al. (2015), the manuscript concluded that "CRUST1.0 has a better spatial resolution" (Page 5, line 15). On the contrary, in my view, the comparison of the manuscript only demonstrated that CRUST1.0 has no valid information on Antarctic interior. Seismic studies under GAMSEIS and POLENET projects since 2007 have shown that the crust of Antarctic interior is very different from previously imagined. The results of GAMSEIS project are overviewed by An et al. (2016) (http://www.aps-polar.org/paper/2016/27/02/A160908000001). Body-wave receiver function (RF) analysis is a good method to detect Moho depth beneath seismic stations and the results are normally considered as reliable. RF studies showed that crust in central East Antarctica is thick (>50 km and even to be ˜60 km) (Hansen et al., 2010; Feng et al., 2014), in West Antarctica is thin (˜20-30 km) (Chaput et al., 2014). However, in CRUST1.0 model, the crust in west Antarctica is >30 km thick, and in East Antarctica is <42 km (Figure 8d). The text ("The comparison with the CRUST1.0 model reveals large differences between them. As seen in Figure 3, from -26 to +19 km, AN1 has higher values, mainly localized in the East Antarctic craton. West Antarctica is much thinner " in " the AN1 model") and Figure 8d in the manuscript shows that AN1 is compatible with the RF studies. From these comparison, we can just conclude that AN1 is more reliable. It is opposite with that "CRUST1.0 has a better spatial resolution".

The Hansen et al. (2010) study is local and focused on the GSM (Gamburtsev Subglacial Mountains). Their results shown that the mean crust thickness estimated in the stations surrounding the GSM is about 40-45 km and reach 55-58 km at the GSM. In our study we show that the crustal thickness over GSM derived from GOCE are around 40-50 km (see figure 5 of our paper) which is consistent with other gravimetric studies (Block et al. 2009, Von Freese et al. 1999, Llubes et al. 2006). However these results are different from those based on GAMSEIS data (Hansen et al. 2010, Feng et al. 2014) .

We have changed the text "*CRUST1.0 has a better spatial resolution*" into: " Including gravimetric observations (land and/or satellite) as constraints of the seismological model allows to improve the spatial resolution".

An:" Another comparison ("The latter seems also rougher, with a less precise coast limit. CRUST1.0 has a better spatial resolution.") is meaningless. Spatial resolution of a model is controlled by observations, but is not related with roughness of the model. More "precise coast limit" in CRUST1.0 indicates that the model around coast areas of Antarctica may be constrained mostly by topography but not seismic observations. The roughness in the model of AN1 around the coast lines is related to its resolution.

Figure S3 in Auxiliary material of An et al. (2015) can be taken as resolution-length map of crustal thicknesses of AN1. The figure shows that the resolution length for crustal thicknesses in AN1 is ˜120 km in Antarctica. This resolution length is similar to that (77-˜200 km) of gravity data used in this manuscript."

We have changed the text *"The latter seems also rougher, with a less precise coast limit."* into: "The roughness in the AN1 model around the coast line is related to its resolution ".
In fact, our paper shows that the crustal thickness model derived from GOCE is closer to CRUST model. But we agree with the reviewer's comment. Our purpose was just to explain models difference, but it is not the main goal of our paper.

The comparison of our results with AN1 model allows us to demonstrate the interest of taking into account gravity data as constraint in crustal thickness models, because it is the most recent model derived from only seismological observations. Firstly, we can confirm/validate spatial variations over the regions where gravimetric and seismological signals are comparable, and highlight the regions where discrepancies exist between the two approaches. Secondly, the use of gravity data improves the model resolution and makes it possible to estimate density variations. We would like to emphasize that GOCE observations have a uniform resolution and accuracy over the whole area covered by the satellite

(2) An : "The manuscript used the thickness of CRUST1 as constraints to analyze gravity observations. "In areas where there is a lack of seismic observations crustal thickness is constraint by gravity observations using maps from British Antarctic Survey (Laske private communication)" (page 5, lines 6-8). In this case, the results for those areas in the manuscript are little significant because the constraints at those areas used in this study of gravity observations are from gravity observations, and their reliability is unknown."

We have focused our approach on a regional comparison between crustal thickness models, i.e., over the entire Antarctica continent. In addition, CRUST1.0 model is not constrained by gravity observations from satellite missions. In the case of local studies, we could use complementary land gravity measurements to improve the spatial resolution but it is not the purpose of this paper.

(3) An : "The very-thick crust in central EANT and very-thin crust in WANT may indicate that Antarctica is special. Density may be also special in the areas. Gravity observations may be useful to detect this."

Yes, we agree, this is shown in figure 9 of our paper.

Biblio :

We agree to add references proposed by M. An work, and we did the technical corrections.

An: "Line 10: "another crustal model has been proposed by a Chinese team" ==> "a regional model on Antarctic crust (AN1) (An et al., 2015) has been proposed". The AN1 model is one of results of the efforts from international (US, China, France, Japan) collaborations under GAMSEIS and partly under POLENET. The model AN1 is a regional model, but CRUST1.0 is a global model."

Ok, we changed the text

An: "Lines 11-12: delete "but in Antarctica there are very few seismological observations and the Chinese model is poorly constrained" Line 15: delete "CRUST1.0 has a better spatial resolution"

We changed the text. See comment about R2 remarks.

An : "Page 7 Lines 3-5: "According to previous studies (Block et al., 2009; Ritzwoller et al., 2001), the mean depth in West Antarctica is about 40 km and in East Antarctica is about 30 km. We fix to the mean value, 35 km, as mean depth for the whole continent" ==> "According to global 1-D model of AK135 (Kennett et al., 1995), we fix to the mean value, 35 km, as mean depth for the whole continent". The studies (Ritzwoller et al., 2001; Block et al., 2009) did not use new seismic observation or results. It is not true that "the mean depth in West Antarctica is about 40 km and in East Antarctica is about 30 km". Since only a general mean value (35 km) is used, it is acceptable to cite a global 1-D model of AK135."

We do not say 35 km is the real mean thickness of the crust in Antarctica. We only use this value to start our computation. And we choose a realistic value, in agreement with scientific literature. AK135 is an old reference (Kennett et al., 1995). We prefer to cite the reference to AN's model (2015), which is in agreement with our starting value (see table 1 of this manuscript).

RESPONSE TO R2 :

R2 :"It has several problems, some of which stem from the poor documentation of CRUST1.0."

We agree that CRUST1.0 is poorly documented. We contacted G. Laske and asked for some details. She answered "Ice thickness was constrained using maps from the British Antarctic survey", but she did not confirm whether space gravimetric data have been included or not in the model. This is the reason why we wanted to compare with a fully independent model, like AN.1. Our aim was to show that gravimetry can constrain the crustal models and help to have a better solution than models using only seismology data.

R2: "To have confidence in the work more assessment is needed (e.g. a comparison with receiver functions)"

We take into account this possibility. We propose to merge figure 6 and figure 7 into a new figure 6. Then, figure 8 becomes figure 7 and the new figure 8 shows the comparison with receiver functions for the crustal thickness (we respect the limit of 10 figures max.). This comparison is a very local test. Don't forget our model is a global and a rough resolution solution.

The text of the manuscript has been changed: we added a new paragraph at the end of **5.2.2 Spatial analysis of crustal models** (page 11, line 22). This paragraph is entitled: "Comparison with seismic receiver functions »

Copy of the new paragraph :

Comparison with seismic receiver functions

To complete the confrontation with seismic crustal thicknesses, we compare our results to those from receiver functions. We use the Antarctic Moho compilation given by An (Figure 4 and Table S1 from An et al., 2015), who selected a list of stations under the evaluation of the quality of Moho depth (more details and sources can be found in the publication of An). On Figure 8, we plot the differences between the crustal thickness from GOCE and the value found in the fourth column of Table S1. Roughly, we obtain the same discrepancies than those observed with the profiles on Figure 7. In East Antarctica, our model is thinner than seismic studies (see for example Feng et al., 2014; Hansen et al., 2010). The larger disagreement is located around the Gamburtsev Subglacial Mountains region (GSM). Seismic data show a thickening up to 60-65 km in this region (see also An et al., 2016), while gravity suggest a more regular crust with thicknesses under 50 km.

Conversely, in West Antarctica seismic studies find between 20 and 30 km for the crust thickness which is thinner than our crust from space gravity (Figure 8). Using receiver functions from POLENET, Chaput et al. (2013) explain that this thin crust is compatible with mantle compensation, especially across MBL dome (Marie Byrd Land). During our computation at continental scale, we had to postulate the full crustal isostatic compensation of topography. In regions with mantle compensation or with density variations, our results will differ from the real crustal thickness. Specific studies have to be done in such regions, based on seismic data but also on airborne (Scheinert and al., 2016) or ground gravity data, these latter having a better resolution appropriate to local studies.

R2 : "And addressing non-isostatic support of topography)."

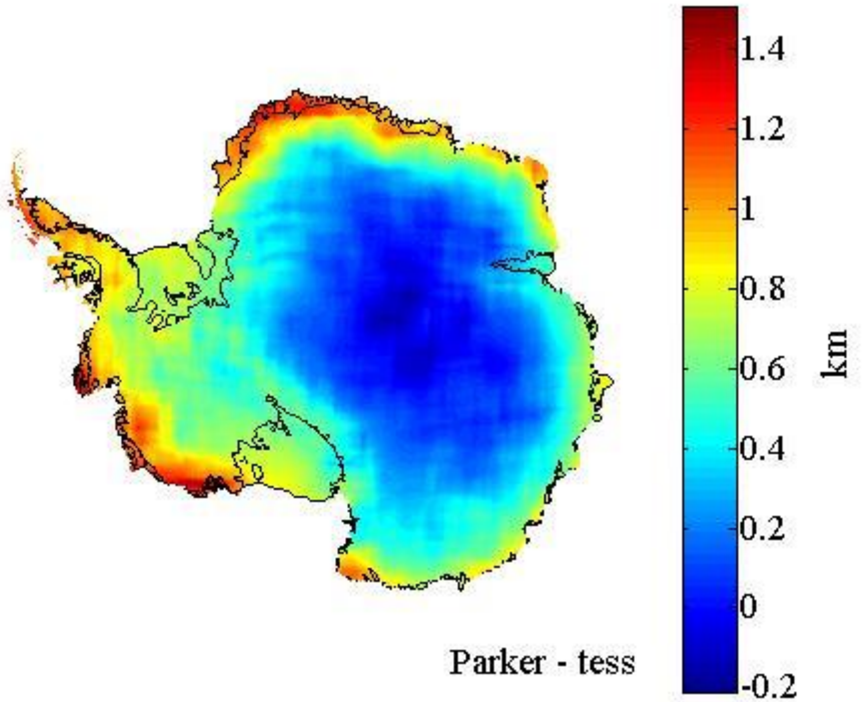
We will reply to this comment below.

R2:"English: in general, the English is not good"

We already contacted the editing service.

R2:"Limits of Parker's method: the authors use Parker's method for deriving the terrain effect, which is appropriate for a flat plane, but may become problematic at scale where curvature is important; this should be justified at this length scale"

We have also estimated terrain effects using tesseroids (Uieda, L., V. Barbosa, and C. Braitenberg (2016), Tesseroids: Forward-modeling gravitational fields in spherical coordinates, GEOPHYSICS, F41-F48, doi:10.1190/geo2015-0204.1.), a method which takes curvature into account. The differences between crustal thickness estimates from Parker or tesseroids methods are shown in the figure below. The maximum reaches 1km, which is within our error bar.



R2:"Airborne gravity: the new compilation of airborne gravity by Scheinert 2016, should be at least mentioned"

We add a comment in the text and mention the publication (page 12, line 10):

"Specific studies have to be done in such regions, based on seismic data but also on airborne (Scheinert and al., 2016) or ground gravity data, these latter having a better resolution appropriate to local studies."

R2:"CRUST 1.0 circularity: the biggest issue is the comparison with CRUST1.0. The authors use old studies for mean crustal thickness constraint, which presumably was an input for CRUST1.0, admit that CRUST1.0 used airborne gravity for input, in some unspecified way (even though they reject Bedmap2 because of its gravity contamination) and come up with the same result as CRUST1.0 which is not that shocking in retrospect"

Our mean value of 35 km is consistent with old studies cited in the text but in fact it is also consistent with AN1 mean value (see table 1 of the paper). CRUST 1.0 used airborne gravity for input in complement of seismic data. This is not a problem because we have been working with GOCE which is only satellite gravity observations. In Bedmap2, GOCE data are used in some regions of Antarctica to constrain the ice thickness, and this is a problem because we are using the same data to obtain the crust thickness.

R2:"In general, CRUST1.0 is not well documented enough to determine how independent of the satellite gravity data it is."

Yes we agree that CRUST 1.0 is not well documented. We have answered this question in the beginning.

R2:"There is not attempt to compare with receiver functions for Moho depth."

As we said we have made this comparison and it is now included in a new paragraph "Comparison with seismic receiver functions" (page 11, line 22).

R2:"Given all that, the statement that CRUST1.0 is to be preferred seems to be far too strong."

We can make the same analysis using CRUST 2.0. This model cannot include space data like GOCE but the resolution is worse. In the text, we do not state that CRUST1.0 is the best model, we observe that CRUST1.0 is closer to our gravity crustal model.

R2:"Non Moho support: there is no attempt to address flexural or mantle support of topography, something strongly suspected for Marie Byrd Land, and likely an issued for Antarctica, given the thick lithosphere and time varying ice load."

We are talking here about small wavelength features, typically smaller than 200 km (usually, it is accepted that structures larger than 200 km are isostatically compensated). This comment concerns local studies with other sources of information. Certainly, in some regions, we could find disagreement between our gravity interpretation and local studies as Chaput et al. (2013). But our work presents results at larger wavelengths, at the scale of Antarctica. We can't resolve very local structures: GOCE resolution is very close to the 200 km limit, and we want to provide a purely gravimetric, global model. Such a model will be interesting in further studies, looking at a specific region, with complementary data at smaller resolution (for example ground or airborne gravity data, seismic data). The combination of our gravity model with local data could be used to test if the signal comes from crust thickness variations or uncompensated topography. Finally, GOCE provides static gravity field then we cannot study time varying deformations.

The text has been changed. Page 12, line 5, we added:

Conversely, in West Antarctica seismic studies find between 20 and 30 km for the crust thickness which is thinner than our crust from space gravity (Figure 8). Using receiver functions from POLENET, Chaput et al. (2013) explain that this thin crust is compatible with mantle compensation, specially across MBL dome (Marie Byrd Land). During our computation at continental scale, we had to postulate the full crustal isostatic compensation of topography. In regions with mantle compensation or with density variations, our results will differ from the real crustal thickness. Specific studies have to be done in such regions, based on seismic data but also on airborne (Scheinert and al., 2016) or ground gravity data, these latter having a better resolution appropriate to local studies.

R2:"Bedmap2: An additional issue is the use of Lythe 2001 over Fretwell 2013 for the bed topography. Figure 6 demonstrated that the authors know where Bedmap2 is using GOCE data, and certainly BEDMAP was not constrained by any data in those areas anyway. There is no value in not using Bedmap2, if you know which areas do have GOCE contamination."

We think it is important for the reader to see easily the regions where GOCE is used into Bedmap 2 because the crustal thickness estimations in these regions are certainly affected when using Bedmap 2 in the inversion. People who are specifically working in these regions should use crustal gravity models carefully.

Technical issues: Throughout: None of the figures have spatial bars or graticals.

We added spatial bars to the figures.

We made all other technical changes suggested by the reviewer.

We added the 3 references mentioned by the reviewer and we cited them in the text.

5

Crustal Thickness of Antarctica estimated using data from gravimetric satellites.

M. Llubes (1), L. Seoane (1), S. Bruinsma (2) and F. Rémy (3)

(1) Université Paul Sabatier, OMP-GET, UM5563, CNRS/IRD/UPS, 14 Avenue Edouard Belin, 31400 Toulouse, France

(2) CNES, Department of Terrestrial and Planetary Geodesy, 18 avenue Edouard Belin, 31401 Toulouse Cedex 4, France

(3) OMP-LEGOS, UM5566, CNRS/IRD/UPS, 14 Avenue Edouard Belin, 31400 Toulouse, France

Correspondence to: Muriel Llubes (Muriel.Llubes@get.omp.eu)

Abstract. Computing a better crustal thickness model is still a necessary improvement in Antarctica. In this far continent where almost all the rocky surface is covered by the ice sheet, seismic investigations do not reach a sufficient spatial resolution for geological and geophysical purposes. Here, we computed a global map of Antarctic crustal thicknesses based on space gravity observations. The DIR5 gravity field model, built from GOCE and also GRACE gravimetric data, is inverted with the Parker–Oldenburg's iterative algorithm. The BEDMAP products are used to estimate the gravity effect of the ice and the rocky surface. Our result is compared to crustal thickness provided by seismological studies, CRUST1.0 and AN1 models. Although CRUST1.0 shows a very good agreement with our model, the spatial resolution is smaller with gravimetric data. Finally, we adjust the crust/mantle density contrast considering the Moho depth from CRUST1.0 model. In East Antarctica, the density contrast clearly shows higher values than in West Antarctica.

1. Introduction

The surface topography of Antarctica has already been determined precisely by the various altimetric missions ERS1/2, EnviSat, ICESat or Cryosat-2 (Zwally et al., 2002; Rémy and Parouty, 2009; Helm et al., 2014) and more recently SARAL or Sentinel-3 (Verron et al., 2015). Glaciologists could track temporal variations of the surface and estimate the volume changes of the whole ice sheet (Zwally et al., 2011; Flament and Rémy, 2012; McMillan et al., 2014). Since 15 years, space gravimetry provides to the scientific community a complementary tool to observe and follow the distribution of masses inside the Earth. The main advantage is that the gravity observations have a homogeneous accuracy whatever the region of interest, i.e. over mountains, oceans or whole continents alike. Satellites are the only way to have information where gravimetric ground data are lacking. Such observations could provide to the glaciologists the thickness of the ice cover and the temporal tracking of the ice sheet. Launched in 2002, the GRACE mission provides monthly or 10 days temporal grids (Lemoine et al., 2007; Foerste et al., 2008; Landerer and Swenson, 2012). It allows the computation of mass balance, annual or seasonal cycles (Ramillien et al., 2006; Llubes et al., 2007; Peng et al., 2016; Ramillien et al., 2006; Williams et al., 2014). In addition, temporal variations in the gravity field can be used for climate or global change purposes as a contribution to the sea level rise equation (Jacob et al., 2012). Jointly with altimetric data, space gravimetry is used to separate snow and ice contribution (Memin et al., 2014).

Glaciological studies also need the spatial ice thickness patterns, if only to simply estimate the volume of the polar ice sheet. When modelling the ice dynamics a crucial parameter is the ice thickness and all simulations of ice thinning in response to climate forcing include this parameter as a main factor (Ritz et al., 2001). For this reason, the community made a real effort to collect and combine all the available sources of information to compute the most complete maps over Antarctica, named BEDMAP (Lythe et al., 2001). The BEDMAP consortium provides grids of ice-surface elevation, ice thickness and bedrock subglacial topography. However, under the ice surface that covers nearly 99% of Antarctica, ice thickness is still unknown in areas without any ground data. In fact, the unobserved areas represent more than 360000 km^2, and very large regions without any information are in the map. These areas without observations are too large to be interpolated. Satellite gravimetry could fill-in the missing ground data, and can be used to estimate the ice thickness (Fretwell et al., 2013).

Furthermore, as gravimetric observations are influenced by all mass distributions, they can also reveal deeper information, such as the Moho depth. Considering this purpose would be useful to geological studies, and help to understand the formation of the continent. Actually, Antarctica is still the least well-known land area. The scientific community needs improvements of the available crust models, at a continental scale but also at a more detailed scale. Several geological formations, detected in the bedrock surface, could be explained if we know more about the crustal structure. In the past, some studies computed the crustal thickness patterns from previous space gravimetric missions – CHAMP, launched in 2000 (Llubes et al., 2003), and GRACE (Block et al., 2009; Llubes et al., 2003). GOCE, a third satellite mission dedicated to observe to higher spatial resolution of the gravity field with high accuracy, could provide more detailed maps of the Moho limit. The other way to obtain information about this limit is to look at seismology. Some studies already used seismological data to constrain the computation of crustal thickness from gravimetric data (O'Donnell and Nyblade, 2014). But the comparison is limited to a few locations and having a good correlation coefficient between both types of crustal thickness is not trivial. Actually, only space gravimetry can cover the Antarctica continent with a complete and dense dataset.

The aim of this paper is to provide a map of crustal thickness variations of the Antarctica continent based on the most recent combined space gravity field, named DIR5 (Bruinsma et al., 2014). We postulate that subsurface contributions can be properly removed using BEDMAP1the old BEDMAP grids to compute the Moho topography. Then we discuss our choices replacing the gravity field by the only GRACE and LAGEOS model EIGEN-GRGS.RL02bis (Bruinsma et al., 2010) , or preferring BEDMAP2Bedmap2 products. Finally, we compare our crustal thickness map to global models issued from seismological data, CRUST1.0 (Laske et al., 2013) and AN1 (An et al., 2015). The CRUST1.0 model allowed us to adjust the density of the crust in Antarctica and to map its variations.

2. Datasets

2.1 Gravity field solutions

European Space Agency's (ESA) first Earth Explorer mission GOCE, Gravity field and steady state Ocean Circulation Explorer (Drinkwater et al., 2003), was launched on 17 March 2009 and reentered the atmosphere on 11 November 2013. The Science Mission lasted from 1 November 2009 to 22 October 2013. GOCE was dedicated to mapping the static gravity field with a high spatial resolution of 100 km, which required measuring from a low altitude of about 250 km.

Data from GOCE (gravity gradients), LAGEOS 1/2 and GRACE were combined in the last release DIR5 (Bruinsma et al., 2014) in order to obtain a high accuracy gravity field model over the entire spectral range. This model is provided in terms of spherical harmonics up to degree 300, but was used in this study to degree 260, i.e. 77 km of spatial resolution.

Due to the inclination of GOCE satellite, the polar regions cannot be observed. In the case of Antarctica, GOCE can only cover the continent above 83.3°S of latitude. Then, we must to notice that when we use the combined model DIR5, the signal observed below this limit latitude value is obtained by GRACE.

For our study, we computed a regular 0.25°x0.25° spatial grid of free air gravity anomalies over the Antarctica continent with the DIR5 model, which is displayed in Figure 1. The gravity anomalies have amplitudes between -120 and 111 mgal (more statistical data are provided in Table 1).

In this paper we have also used the only GRACE and LAGEOS mean gravity field model EIGEN-GRGS.RL02bis (Bruinsma et al., 2010). This gravity field model is also provided in terms of spherical harmonics up to degree 160 i.e 125 km of spatial resolution.

2.2 BEDMAP ~~1 and 2~~ models.

~~BEDMAP2~~Bedmap2 products (Fretwell et al., 2013) consist of grids describing surface elevation, ice-thickness, the seafloor and subglacial bed elevation of the Antarctic south of 60 degrees south. These products were made incorporating all available geophysical data. More details of Antarctica subglacial landscape are visible than in the previously model ~~BEDMAP1~~BEDMAP (Lythe et al., 2001) and the improved data coverage reveals the full scale of mountain ranges, valleys, basins and troughs. Each dataset is projected in Antarctic Polar Stereographic projection, latitude of true scale 71 degrees south, datum WGS84. All heights are in meters relative to mean sea level as defined by the EIGEN-GL04C geoid (Foerste et al., 2008). The ice thickness, bed and surface elevation grids are provided at uniform 1-km spacing.

In this analysis GOCE data is used to estimate ice thickness over the regions where observations lack. We use ice thickness given in the previous release, ~~BEDMAP1~~BEDMAP. With the aim to represent the same range of wavelengths as the gravimetric anomalies, we filtered the difference between both ice thickness estimates to the maximum spatial resolution of GOCE, in this study 77 km. We notice that this difference is mainly at high and mean wavelengths (see Figure 2). The maximum is 1628 m, the minimum is -896 m, and the mean difference is 19 m. The new ~~BEDMAP2~~Bedmap2 seems to improve the ice thickness all over the continent. A more complete comparison between both products is given by (Hirt, 2014).

Thanks to our procedure the Antarctica models and gravity observations remain independent. Finally, in order to have coherent bedrock, it is calculated as the difference of the most precise topography from ~~BEDMAP2~~Bedmap2 and ice thickness from ~~BEDMAP1~~BEDMAP.

2.3 Crustal thickness models from seismology

CRUST1.0 is 1-by-1 degree global crustal model (Laske et al., 2013). This model is an upgrade of the previous model CRUST1.0 including crustal thickness from new active seismic observations. In areas where there is a lack of seismic observations crustal thickness is constraint by gravity observations using maps from British Antarctic Survey (Laske private communication). Baranov and Morelli (2013) in a Moho's depth map compiling geophysical data pointed out disagreements with CRUST1.0. The new version of this crust model may solve the problem.

Recently, ~~another crustal~~a regional model on Antarctic crust, AN1, has been proposed~~ by a Chinese team~~ (An et al., 2015). This model is based exclusively on seismic observations. This will provide us an independent tool for comparison with our result from gravity data~~, but in~~. In Antarctica there are very few seismological observations ~~and~~compared to gravity data, for example, in areas of East Antarctica as QML (Queen Maud Land) and AGV (George V land) (see Kanao et al. 2013 figure 1 to see the ~~Chinese model is poorly constrained.~~station distribution or An et al. 2015 figure 4). The comparison with the CRUST1.0 model reveals large differences between them. As seen in Figure 3, from -26 to +19 km, AN1 has higher values, mainly localized in the East Antarctic craton. West Antarctica is much thinner than the AN1 model. ~~The latter seems also rougher, with a less precise coast limit. CRUST1.0 has a better~~The roughness in the AN1 model around the coast line is related to its resolution. Including gravimetric observations (land and/or satellite) as constraints of the seismological model allows to improve the spatial resolution.

3. Direct problem: terrain gravity effects.

In order to estimate the gravity anomalies mainly due to crustal thickness variations, we computed by Parker method (Parker, 1973) the gravitational terrain effects using ~~BEDMAP1~~BEDMAP ice thickness, and sea depth and surface topography from the ~~BEDMAP2~~Bedmap2 model. In our case, the Parker approach is the most adequate due to the improved spatial resolution obtained using GOCE observations. When the spatial resolution is less than 300 km we are not in the conditions to make a simple the Bouguer approach to estimate gravity effects. Parker proposes to use Fourier transforms to calculate the gravitational anomaly caused by an uneven, non-uniform layer of material.

To simplify the computations, the rock equivalent topography is calculated as (Balmino et al., 2012; Hirt, 2014):

$$H_r = H_b + \frac{\rho_o}{\rho_r} H_o + \frac{\rho_i}{\rho_r} H_i \qquad (1)$$

Where H_r is the rock equivalent topography, H_b is the bedrock topography, H_o is the ocean depth, H_i ice thickness, ρ_r is the rock density (2.670), ρ_o is the sea water density (1.03) and ρ_i is ice density (0.917).

Using Parker's method computed by Simmons as a MATLAB function (http://geoweb.princeton.edu/people/simons/software.html), we estimate the terrain gravitational effects by considering only one interface of constant density ρ_r with a topography given by eq. (1). The resulting gravitational effect filtered to GOCE spatial resolution on the pole, (i.e., around 77 km) is shown in Figure 4a.

The difference between anomalies derived from GOCE and terrain effects gives the Bouguer anomaly essentially due to crustal thickness variations. However, there are also included the errors in layer's thickness given by BEDMAP ~~1~~ and ~~2~~Bedmap2 models. At large spatial wavelengths, there could be geophysical signal from upper mantle that would nether be taken into account during this study. Bouguer anomalies are shown in Figure 4b.

The statistical information on GOCE free air anomalies, gravitational terrain effects and Bouguer anomalies are given in Table 1. The gravity anomalies obtained by GOCE show variations between -120 and 110 mgal. The Bouguer anomalies give variations between -250 and 360 mgal, with a very different pattern. On Figure 4b, there is a large discrepancy between the eastern part and the western part of the continent that may reflect the geological history of Antarctica. There are also a lot of details at higher resolution coming from the low degrees of spherical harmonics in GOCE gravity field. The inversion of these Bouguer anomalies will help us to better understand the crustal structure.

4. **Inverse problem: crustal thickness estimation.**

To obtain crustal thickness variations from the Bouguer anomalies inferred from GOCE observations and BEDMAP estimates (see section 3), we resolve the inverse problem using the Parker–Oldenburg iterative algorithm. To this purpose we use the 3dinver MATLAB function proposed by (Gómez-Ortiz and Agarwal, 2005). This algorithm allows computing the 3D topography of a constant density layer.

To solve the inverse problem, we must fix as input the density contrast and the mean depth of the layer. Considering that the mantle density is 3.3, we choose a density contrast of 0.63 to be coherent with our gravity terrain effects computation (rock density 2.670). According to previous studies (Block et al., 2009; Ritzwoller et al., 2001; An et al., 2015), the mean depth in West Antarctica is about 40 km and in East Antarctica is about 30 km. We fix to the mean value, 35 km, as mean depth for the whole continent for the starting computation.

A higher-cut filter is required to ensure convergence of the inverse problem (see section 2, Gómez-Ortiz and Agarwal, 2005). In our case this filter restricts frequency contents between wavelengths of 77 km and 100 km.

In order to provide information about the accuracy of the inversion, the 3Dinver program computes additionally the difference between the gravity effect of the output layer's topography and the observed Bouguer anomalies used as input. The RMS is only about 5 mgal indicating a satisfactory accuracy.

The computed crustal thickness is shown in Figure 5. Spatial variations from 29.7 to 51 km can be observed, with a mean thickness value of 41 km (see Table 1). This last is slightly stronger than the mean value of both seismological models because for these models we kept some oceanic crust in the estimation of the mean thickness. The AN1 model has a higher standard deviation compared to the others. This may come from a few geographical areas with a high noise level.

As it was already confirmed in several previous studies, Antarctica is separated into two unequal parts, testifying to the complex formation of this continent. The TransAntarctic Mountains (TAM, Figure 5) delimit the border between the thick East Antarctica (EA) and the thin West Antarctica (WA). This last one is constituted by a complicated assemblage of geological structures, still under study (Lindow et al., 2016; Heeszel et al., 2016). The Peninsula (P) and the Marie ~~Bird~~Byrd Land (MBL) have the highest crustal thickness of this continental part, reaching 45 km in some places. The rest of the zone is mainly thinner than 35 km. East Antarctica's structure and history are better understood. Geological, geochemical, petrological and isotopic studies (Mikhal'sky, 2008; Dasgupta et al., 2001) suggested that the eastern part is an old craton made during several tectonic events. Successive deformation phases remodeled this crust over time. For example, in the region of Dronning Maud Land, age data reveal primary Grenvillian rocks which had been intruded by Pan-African igneous episodes (Paech, 2001). Seismic imaging contributes to understanding the evolution of this region (Kanao et al., 2011) and to mapping of variations in the Moho depth. (Bayer et al., 2009) observed a crustal thickening from coast to inland, between 40 km and 51 km. Our gravimetric study confirms this tendency (Figure 5) linked to the continuing thick crust in the central part of East Antarctica, whereas the adjacent region in the west side is thinner. Also in Figure 5, the Lambert Rift (LR) clearly appears in our crustal model, and the enigmatic structure of the Gamburtsev Mountains (GSM) seems to be independent from the surrounding geological pattern. As the origin of these subglacial mountains was poorly known a specific seismic survey had been done (Wolovick et al., 2009). Now, with our global map made from GOCE data, it is possible to follow specific geological details over the whole continent. It can also be useful to develop and analyze an isostatic model in the interpretation of topographic structures (O'Donnell and Nyblade, 2014).

5. Discussion.

5.1 About our choices in the computation of the crustal model

5.1.1 ~~BEDMAP1~~BEDMAP or ~~BEDMAP2~~Bedmap2

When computing the direct gravitational effect, we had to choose a model for all contributing layers. The best grids for the ice thickness – and so for the bedrock elevation – are provided by BEDMAP in the most complete data compilation available. The new version of these products, ~~BEDMAP2~~Bedmap2, also includes (satellite gravity) data from GRACE and GOCE. So we preferred to use the prior version ~~BEDMAP1~~BEDMAP for the ice thickness variations to have a strictly independent grid which allows us to estimate the gravitational effect of the ice. But ~~BEDMAP2~~Bedmap2 incorporates two orders of magnitude more data than ~~BEDMAP1~~BEDMAP, it has a better spatial resolution, coverage and precision at any wavelength. It is interesting to estimate the impact of ~~BEDMAP2~~Bedmap2 in our crustal inversion. We did the same process but using ice thickness from ~~BEDMAP2~~Bedmap2, up to the computation of the crustal thickness. The differences in the both solutions span from -3.7 to +12.2 km, but the standard deviation is only 1.2 (see Table 1 for these statistical data). The higher values are not always located in the areas completed by satellite gravity in ~~BEDMAP2~~Bedmap2, because the large set of new data included during the computation really improved the model. In Figure ~~6~~6a, the ~~blue~~pink line shows the areas for which no ground data available within at least 50 km. We can trust the new version of BEDMAP is closer to reality outside the blue line limit and then our direct estimation is more accurate. Some geological details appear in the crust variations estimate when computed with ~~BEDMAP2~~Bedmap2 ice thickness. The improvement of this version is important, even when dealing with the base of the continental crust. It would be interesting to have a version of this product that does not depend on satellite gravity data.

5.1.2 Profit from GOCE compared to GRACE observations

GOCE is the last of three space missions dedicated to gravity field modeling. In a lower altitude orbit equipped with a gradiometer, it measured smaller details of the gravity field. The GRACE mission was launched at a higher altitude, mainly to observe the temporal variations. But thanks to its long and still ongoing mission, it is also possible to compute an accurate geoid. The spatial resolution is less than the geoid obtained with GOCE, but we could evaluate the differences in our crust estimate from one or the other. Additionally, we hope to see crustal details in the 77 – 120 km wavelength band. It should be noted that the GOCE geoid grid is a combined solution incorporating GRACE data.

The difference between the both crustal thickness, from only GRACE model EIGEN-GRGS.RL02bis and from GOCE DIR5 gravity anomalies, clearly shows a high frequency signal, corresponding to the contribution of GOCE at small spatial scales. The discrepancies span between ±7 km, emerging from the ambient noise level. They are mainly located over the Transantarctic Mountains (TAM), the peninsula (P), and in the western part of the continent. In East Antarctica (EA), both models are really closed. The differences do not exceed 2 km, except in the Lambert Rift (LR) – see Figure 5 for location of TAM, P, EA and LR. The new GOCE DIR5 version should provide interesting details for geological interpretation and the knowledge of Antarctica structure.

5.2 Comparison with models using seismology observations

5.2.1 The entire maps

We already compared both models issued from the seismology community (see Sect. 2.3). Clearly, CRUST1.0 looks closer to our result. We computed the difference between them and plotted the corresponding map (Figure 76b). Doing the same with the AN1 model will give differences identical to those between CRUST1.0 and AN1 because they dominate: the latter model is far from the two others.

The crustal thickness computed in this paper is on average 1.2 km higher than for the CRUST1.0 model. The larger discrepancies are located all around the Antarctica continent, because the two coast limits can differ. We also note that our crust is thinner in the TransAntarctic Mountains, in some regions of West Antarctica and in the center of East Antarctica. CRUST1.0 has smaller amplitude variations, the lowest and highest values are reached by our model (see Table 1 for statistical results).

5.2.2 Spatial analysis of crustal models

Spectral study

We computed the power spectral densities of the crustal thickness. They are shown in Figure 87.a from 0 to 1000 km for crustal thickness obtained from GOCE data, from GRACE data, for crustal thickness given by the CRUST1.0 model and by AN1.

Finally, there are very few differences at any wavelength between thickness from GOCE DIR5 model and the one from only GRACE EIGEN-GRGS.RL02bis model. This confirms the remark made in Sect. 5.1.2 about their very small spatial differences. Because GOCE DIR5 grids also incorporate GRACE data, they are naturally close to another. Except when looking at wavelengths smaller than 120 km, where the differences should be stronger. The additional improvement by GOCE data at small wavelength is not really evident.

Comparing gravity-derived and seismological models, a clear discrepancy appears between them even if the global tendency is the same. The spectral densities show more energy for crustal thickness derived from gravity observations (Figure ~~8~~7.a).

In fact, we worked with the complete gravitational signal to inverse the crustal thickness. We certainly included effects from the subjacent mantle in this interpretation. These effects have a long wavelength pattern, but there is no specific signal in the spectral curve. Seismological models are not affected by these effects and they share the same behavior at short wavelength. There is no evidence for mantellic disturbance in our result of crustal thickness. Anyway, it is not possible to isolate and correct it during the computation process.

Profiles tracking

With the aim to compare more easily the crustal models, on Figure ~~8~~7 four profiles have been extracted along a geographical path (b). They are respectively oriented S-N (c), W-E (d), NW-SE (e) and SW-NE (f). The main differences appear first over the oceans and over the two ice shelves because our inversion method is not adapted to these regions (we cut a part of the plots on Figure ~~8~~7). Secondly, there are large discrepancies near the coast limit which is not the same for all models.

On the continent, CRUST1.0 is very close to our results, but it always has smaller thickness values. But as we had to choose a mean depth to compute the Moho's spatial variations, this difference is not relevant. Looking at the four plots, we see a higher discrepancy in the North and West parts of the continent. For example, in Dronning Maud Land, CRUST1.0 gives a thinner crust than our models. Smaller scale variations are visible in the GOCE DIR5 and GRACE EIGEN-GRGS.RL02bis profiles, while CRUST1.0 is smoother.

Clearly, AN1 is very different from the three others. It shows less spatial details, with a more constant profile along west Antarctica. In the Gamburtsev Subglacial Mountains region, the model reaches it maximum with a sudden thickening up to 65 km, over a very restrictive area (Figure ~~8~~7.d). No other model shows such a local thick crust. For the moment, persons working with a seismic crustal model would prefer CRUST1.0 which is validated by gravity crustal models.

Comparison with seismic receiver functions

To complete the confrontation with seismic crustal thicknesses, we compare our results to those from receiver functions. We use the Antarctic Moho compilation given by An (Figure 4 and Table S1 from An et al., 2015), who selected a list of stations under the evaluation of the quality of Moho depth (more details and sources can be found in the publication of An). On Figure 8, we plot the differences between the crustal thickness from GOCE and the value found in the fourth column of Table S1. Roughly, we obtain the same discrepancies than those observed with the profiles on Figure 7. In East Antarctica, our model is thinner than seismic studies (see for example Feng et al., 2014; Hansen et al., 2010). The larger disagreement is located around the Gamburtsev Subglacial Mountains region (GSM). Seismic data show a thickening up to 60-65 km in this region (see also An et al., 2016), while gravity suggest a more regular crust with thicknesses under 50 km.

Conversely, in West Antarctica seismic studies find between 20 and 30 km for the crust thickness which is thinner than our crust from space gravity (Figure 8). Using receiver functions from POLENET, Chaput et al. (2013) explain that this thin crust is compatible with mantle compensation, specially across MBL dome (Marie Byrd Land). During our computation at continental scale, we had to postulate the full crustal isostatic compensation of topography. In regions with mantle compensation or with density variations, our results will differ from the real crustal thickness. Specific studies have to be done in such regions, based on seismic data but also on airborne (Scheinert and al., 2016) or ground gravity data, these latter having a better resolution appropriate to local studies.

5.2.3 Density estimation

In our computation, we chose a 0.63 density contrast because it was coherent with previous studies and a very classical choice in such geological context. Recently, O'Donnell and Nyblade (2014) proposed a smaller contrast of 0.3 when they adjusted the crustal thickness based on gravimetric data to seismological results. Therefore, it was important to reconsider the density of the crust and the upper mantle in Antarctica. We decided to use a simple Bouguer formula to estimate the density contrast variations, assuming that the observed Bouguer anomalies are mainly due to density variations that are not considered in the STGE. The Bouguer anomaly map is filtered to 333 km, and we chose the CRUST1.0 model for the crustal thickness. The result is shown in Figure 9 and it represents the variations around the crust's mean density value of 2.67 when mantle density is fixed at 3.3. We notice that the density is slightly smaller in the western part of the continent. Few spatial variations are visible on Figure 9. Density seems to be constant enough, from 2.72 to 2.8 in East Antarctica and from 2.62 to 2.75 in West Antarctica. Geological studies in this last region indicate a complex assembly, made by several tectonic plates, thinner and younger than the old eastern craton, explaining the density discrepancy. This is coherent with the results of (Tenzer and Bagherbandi, 2013), except in Marie ~~Bird~~Byrd Land where we found an increase of density not visible in their study. However, gravimetric observations do not need spatially varying density to be interpreted. A constant density contrast is a good first hypothesis to compute the inversion of the Bouguer anomalies and obtain the crustal thickness.

6. Conclusion.

We have provided a global map of crustal thickness, displayed in Figure 5, covering the entire Antarctic continent. Thanks to the new GOCE gravity field model, a spatial resolution of 77 km is reached with almost the same accuracy anywhere. Compared to previous studies, smaller details appear on the map, and the noise level is lower because we used the last available gravity grids which compile all GRACE and GOCE data. However, the ice thickness estimation remains a key parameter during the process. An improved ice thickness map, made from satellite observations and fully independent from gravity data, would benefit not only glaciological but also our crustal studies.

Currently, comparing our result to seismological models shows a fairly good agreement. Some studies already tried to use seismic observations to constrain the thickness derived from gravimetry, and seismological models begin to include gravimetric observations. Next, a joint inversion of seismological and gravimetric data, including data from satellite missions, will provide the next crustal model of Antarctica.

All studies concern long spatial wavelength, barely better than 100 km. Geophysical and geological studies need a higher spatial resolution to understand the crust structure over more local regions. Antarctica is still the Earth's place where the crust is least known. It will be a real challenge to improve the crustal model resolution even if only for specific areas. Maybe additional gravity campaigns or satellite missions will allow this progress.

Our computed crustal thickness models of Antarctica will be available on the web The International Gravimetric Bureau website (http://bgi.omp.obs-mip.fr/).

Acknowledgements

We want to thanks G. Laske for the information she provided to us about CRUST1.0 model. This work has been supported by University Paul Sabatier (Observatoire Midi-Pyrénées) and the French space agency CNES.

References

An, M., Douglas, A.W., and Zhao, Y.: A frozen collision belt beneath ice: an overview of seismic studies around the Gamburtsev Subglacial Mountains, East Antarctica, Advances in Polar Science, 27(2), 78-89, 2016.

An, M., Wiens, D. A., Zhao, Y., Feng, M., Nyblade, A. A., Kanao, M., Li, Y., Maggi, A. and Leveque, J.-J.: S-velocity model and inferred Moho topography beneath the Antarctic Plate from Rayleigh waves, J. Geophys. Res.-SOLID EARTH, 120(1), 359–383, doi:https://doi.org/10.1002/2014JB011332, 2015.

Balmino, G., Vales, N., Bonvalot, S. and Briais, A.: Spherical harmonic modelling to ultra-high degree of Bouguer and isostatic anomalies, J. Geod., 86(7), 499–520, doi:10.1007/s00190-011-0533-4, 2012.

Baranov, A. and Morelli, A.: The Moho depth map of the Antarctica region, Tectonophysics, 609, 299–313, 2013.

Bayer, B., Geissler, W. H., Eckstaller, A. and Jokat, W.: Seismic imaging of the crust beneath Dronning Maud Land, East Antarctica., Geophys. J. Int., 178(2), 860, doi:10.1111/j.1365-246X.2009.04196.x, 2009.

Block, A. E., Bell, R. E. and Studinger, M.: Antarctic crustal thickness from satellite gravity: Implications for the Transantarctic and Gamburtsev Subglacial Mountains, Earth Planet. Sci. Lett., 288(1–2), 194–203, doi:https://doi.org/10.1016/j.epsl.2009.09.022, 2009.

Bruinsma, S., Lemoine, J.-M., Biancale, R. and Valès, N.: CNES/GRGS 10-day gravity field models (release 2) and their evaluation, Adv. Space Res., 45(4), 587–601, doi:10.1016/j.asr.2009.10.012, 2010.

Bruinsma, S. L., Förste, C., Abrikosov, O., Lemoine, J.-M., Marty, J.-C., Mulet, S., Rio, M.-H. and Bonvalot, S.: ESA's satellite-only gravity field model via the direct approach based on all GOCE data, Geophys. Res. Lett., 41(21), 7508–7514, doi:10.1002/2014GL062045, 2014.

Chaput, J., Aster, R., C., Huerta, A., Sun, X., Lloyd, A., Wiens, D., Nyblade, A., Anandakrishnan, S., Winberry, J. P., and Wilson, T.: The crustal thickness of West Antarctica, J. Geophys. Res., 119 (1), 378-395, doi:10.1002/2013JB010642, 2013.

Dasgupta, S., Sengupta, S., Bose, S., Fukuoka, M. and Dasgupta, S.: Polymetamorphism in the Schirmacher Hills Granulites, East Antarctica: Implications for Tectonothermal Reworking of an Isobarically Cooled Deep Continental Crust, Gondwana Res., 4(3), 337, doi:10.1016/S1342-937X(05)70334-8, 2001.

Drinkwater, M., Floberghagen, R., Haagmans, R., Muzi, D. and Popescu, A.: GOCE: ESA's first Earth Explorer Core mission, SPACE Sci. Rev., 108(1–2), 419–432, doi:10.1023/A:1026104216284, 2003.

Flament, T. and Rémy, F.: Dynamic thinning of Antarctic glaciers from along-track repeat radar altimetry, J. Glaciol., 58(211), 830–840, doi:10.3189/2012JoG11J118, 2012.

Feng, M., An, M., An, C., Shi, G., Zhao, Y., Li, Y., and Wiens, D.: Crustal thicknesses along the traverse from Zhongshan to Dome A in east Antarctica (in Chinese with English abstract), Chinese J. Polar Research, 26(2), 177–185, 2014

Foerste, C., Schmidt, R., Stubenvoll, R., Flechtner, F., Meyer, U., Koenig, R., Neumayer, H., Biancale, R., Lemoine, J.-M., Bruinsma, S., Loyer, S., Barthelmes, F. and Esselborn, S.: The GeoForschungsZentrum Potsdam/Groupe de Recherche de Geodesie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C, J. Geod., 82(6), 331–346, doi:10.1007/s00190-007-0183-8, 2008.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C. and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7(1), 375–393, doi:10.5194/tc-7-375-2013, 2013.

Gómez-Ortiz, D. and Agarwal, B. N. P.: 3DINVER.M: a MATLAB program to invert the gravity anomaly over a 3D horizontal density interface by Parker–Oldenburg's algorithm, Comput. Geosci., 31(4), 513–520, doi:10.1016/j.cageo.2004.11.004, 2005.

Hansen, S. E., Nyblade, A. A., Heeszel, D. S., Wiens, D. A., Shore, P., and Kanao, M.: Crustal structure of the Gamburtsev Mountains, East Antarctica, from S-wave receiver functions and Rayleigh wave phase velocities, Earth Planet. Sci. Lett., 300(3- 4), 395–401, doi:https://doi.org/10.1016/j.epsl.2010.10.022, 2010

Heeszel, D. S., Wiens, D. A., Anandakrishnan, S., Aster, R. C., Dalziel, I. W. D., Huerta, A. D., Nyblade, A. A., Wilson, T. J. and Winberry, J. P.: Upper mantle structure of central and West Antarctica from array analysis of Rayleigh wave phase velocities, J. Geophys. Res. Solid Earth, 121(3), 1758–1775, doi:10.1002/2015JB012616, 2016.

Helm, V., Humbert, A. and Miller, H.: Elevation and elevation change of Greenland and Antarctica derived from Cryosat-2, The Cryosphere, 8, 1539–1559, 2014.

Hirt, C.: GOCE's view below the ice of Antarctica: Satellite gravimetry confirms improvements in Bedmap2 bedrock knowledge, Geophys. Res. Lett., 41(14), 5021–5028, doi:10.1002/2014GL060636, 2014.

Jacob, T., Wahr, J., Pfeffer, W. T. and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482(7386), 514–518, doi:10.1038/nature10847, 2012.

Kanao, M., Fujiwara, A., Miyamachi, H., Toda, S., Ito, K., Tomura, M. and Ikawa, T.: Reflection imaging of the crust and the lithospheric mantle in the Lützow-Holm complex, Eastern Dronning Maud Land, Antarctica, derived from the SEAL transects, Tectonophysics, 508(1), 73, doi:10.1016/j.tecto.2010.08.005, 2011.

Landerer, F. W. and Swenson, S. C.: Accuracy of scaled GRACE terrestrial water storage estimates, Water Resour. Res., 48(4), n/a-n/a, doi:10.1029/2011WR011453, 2012.

Laske, G., Masters, G., Ma, Z. and Pasyanos, M.: Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust, Geophys Res Abstr., 15, Abstract EGU2013-2658, 2013.

Lemoine, J.-M., Bruinsma, S., Loyer, S., Biancale, R., Marty, J.-C., Perosanz, F. and Balmino, G.: Temporal gravity field models inferred from GRACE data., J Adv Space Res, doi:10.1016/j.asr.2007.03.062, 2007.

Lindow, J., Kamp, P. J. J., Mukasa, S. B., Kleber, M. and Lisker, F.: Exhumation history along the eastern Amundsen Sea coast, West Antarctica, revealed by low temperature thermochronology, Tectonics, 35(10), 2239–2257, doi:10.1002/2016TC004236, 2016.

Llubes, M., Florsch, N., Legresy, B., Lemoine, J.-M., Loyer, S., Crossley, D. and Rémy, F.: Crustal thickness in Antarctica from CHAMP gravimetry, Earth Planet. Sci. Lett., 212(1–2), 103–117, doi:10.1016/S0012-821X(03)00245-0, 2003.

Llubes, M., Lemoine, J.-M. and Rémy, F.: Antarctica seasonal mass variations detected by GRACE, Earth Planet. Sci. Lett., 260(1–2), 127–136, doi:10.1016/j.epsl.2007.05.022, 2007.

Lythe, M., Vaughan, D. and Consortium, B.: BEDMAP: A new ice thickness and subglacial topographic model of Antarctica, J. Geophys. Res.-SOLID EARTH, 106(B6), 11335–11351, doi:10.1029/2000JB900449, 2001.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A. and Wingham, D.: Increased ice losses from Antarctica detected by CryoSat-2, Geophys. Res. Lett., 41(11), 3899–3905, doi:10.1002/2014GL060111, 2014.

Memin, A., Flament, T., Remy, F. and Llubes, M.: Snow- and ice-height change in Antarctica from satellite gravimetry and altimetry data, EARTH Planet. Sci. Lett., 404, 344–353, doi:10.1016/j.epsl.2014.08.008, 2014.

Mikhal'sky, E. V.: Main stages and geodynamic regimes of the Earth's crust formation in East Antarcica in the Proterozoic and early Paleozoic, Geotectonics, 42(6), 413–429, 2008.

O'Donnell, J. P. and Nyblade, A. A.: Antarctica's hypsometry and crustal thickness: Implications for the origin of anomalous topography in East Antarctica, Earth Planet. Sci. Lett., 388, 143–155, doi:10.1016/j.epsl.2013.11.051, 2014.

Parker, R. L.: The Rapid Calculation of Potential Anomalies, Geophys. J. R. Astron. Soc., 31(4), 447–455, doi:10.1111/j.1365-246X.1973.tb06513.x, 1973.

Peng, P., Zhu, Y., Zhong, M., Kang, K., Du, Z. and Yan, H.: Ice Mass Variation in Antarctica from GRACE Over 2002–2011, Mar. Geod., 39(2), 178–194, doi:10.1080/01490419.2016.1145609, 2016.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E. R., Llubes, M., Remy, F. and Biancale, R.: Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE, Glob. Planet. Change, 53(3), 198–208, doi:10.1016/j.gloplacha.2006.06.003, 2006.

Rémy, F. and Parouty, S.: Antarctic ice sheet and radar altimetry : a review, Remote Sens., 1, 1212–1229, doi:10.3390/rsl1041212, 2009.

Ritz, C., Rommelaere, V. and Dumas, C.: Modeling the evolution of Antarctic ice sheet over the last 420,000 years: Implications for altitude changes in the Vostok region, J. Geophys. Res., 106(D23), 31,943-31,964, 2001.

Ritzwoller, M. H., Shapiro, N. M., Levshin, A. L. and Leahy, G. M.: Crustal and upper mantle structure beneath Antarctica and surrounding oceans, J. Geophys. Res. Solid Earth, 106(B12), 30645–30670, doi:10.1029/2001JB000179, 2001.

Scheinert, M., Ferraccioli, F., Schwabe, J., Bell, R., Studinger, M., Damaske, D., Jokat, W., Aleshkova, N., Jordan, T., Leitchenkov, G., Blankenship, D. D., Damiani, T. M., Young, D., Cochran, J. R., and Richter, T. D., New Antarctic Gravity Anomaly Grid for Enhanced Geodetic and Geophysical Studies in Antarctica, Geophys. Res., Lett., 43, 2, 600-610, doi:10.1002/2015GL067439, 2016.

Tenzer, R. and Bagherbandi, M.: Reference crust-mantle density contrast beneath Antarctica based on the Vening Meinesz-Moritz isostatic inverse problem and CRUST2.0 seismic model, EARTH Sci. Res. J., 17(1), 7–12, 2013.

Verron, J., Sengenes, P., Lambin, J., Noubel, J., Steunou, N., Guillot, A., Picot, N., Coutin-Faye, S., Sharma, R., Gairola, R. M., Murthy, D. V. A. R., Richman, J. G., Griffin, D., Pascual, A., Rémy, F. and Gupta, P. K.: The SARAL/AltiKa Altimetry Satellite Mission., Mar. Geod., 38, 2, doi:10.1080/01490419.2014.1000471, 2015.

Williams, S. D. P., Moore, P., King, M. A. and Whitehouse, P. L.: Revisiting GRACE Antarctic ice mass trends and accelerations considering autocorrelation, Earth Planet. Sci. Lett., 385, 12–21, doi:10.1016/j.epsl.2013.10.016, 2014.

Wolovick, M., Block, A. E., Bell, R. E., Studinger, M., Ferraccioli, F., Braaten, D. A. and Damaske, D.: Preliminary analysis of the Gamburtsev subglacial mountains morphology from AGAP airborne radar data, EOS Trans AGU Fall Meet. Suppl., 90(52) [online] Available from: http://search.ebscohost.com/login.aspx?direct=true&site=eds-live&db=geh&AN=2016-019425 (Accessed 31 July 2017), 2009.

Zwally, H. J., Schutz, B., Abdalati, W., Abshire, J., Bentley, C., Brenner, A., Bufton, J., Dezio, J., Hancock, D., Harding, D., Herring, T., Minster, B., Quinn, K., Palm, S., Spinhirne, J. and Thomas, R.: ICESat's laser measurements of polar ice, atmosphere, ocean, and land, J. Geodyn., 34(3), 405, doi:10.1016/S0264-3707(02)00042-X, 2002.

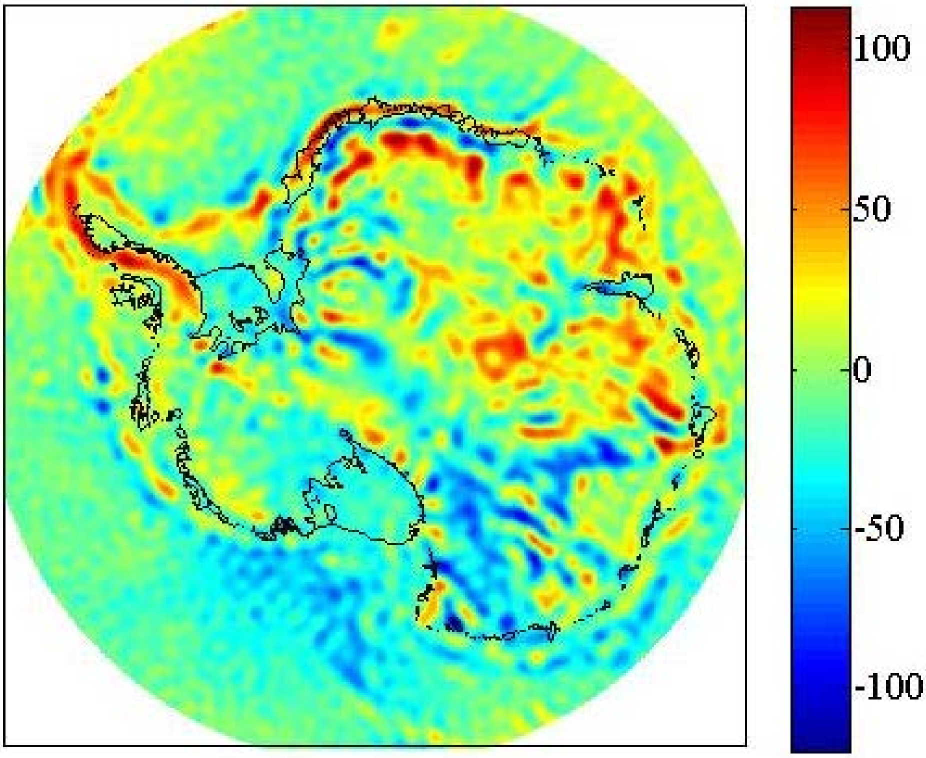
Zwally, H. J., Li, J., Brenner, A. C., Beckley, M., Cornejo, H. G., Dimarzio, J., Giovinetto, M. B., Neumann, T. A., Robbins, J., Saba, J. L., Yi, D. H. and Wang, W. L.: Greenland ice sheet mass balance: distribution of increased mass loss with climate warming: 2003-07 versus 1992-2002, J Glaciol, 57(201), 88–102, 2011.

Formatted: Suppress line numbers, Tab stops: Not at 9.23 cm

Formatted: Suppress line numbers

	Minimum	***Maximum***	***Mean***	***S. D.***
GOCE Free Air Anomaly	-120.0	111.7	-4.2	22.5
Gravity terrain effect*	-371.3	291.5	-64.6	154.2
Bouguer anomaly*	-242.8	373.4	60.4	149.2
CRUST MODEL				
Our crust model	29.7	51.0	40.9	3.4
CRUST1.0 (Laske et al. 2013)	7.5	45.9	35.7	3.4
AN1 (An et al., 2015)	7.9	65.0	35.9	7.6
DIFFERENCE between crust models				
CRUST1.0 – AN1	-26.0	19.0	-0.3	4.2
GOCE ~~Bedmap1~~BEDMAP - Bedmap2	-3.7	12.2	1.3	1.2
GOCE - GRACE	-7.6	7.3	0.0	0.9
GOCE - CRUST1.0	-4.5	29.0	1.2	1.9

Table 1: Statistical data for maps used in this study. The three first rows are in mGal, and the others are in km. The * indicates the application of a 77km low-pass filter.



Formatted: Default Paragraph Font, Font: +Body (Calibri), 11 pt, Bold, English (U.K.)

Formatted: Centered, Line spacing: Multiple 1.08 li

Formatted: Default Paragraph Font, Font: +Body (Calibri), 11 pt, Bold

Formatted: Left, Line spacing: Multiple 1.08 li

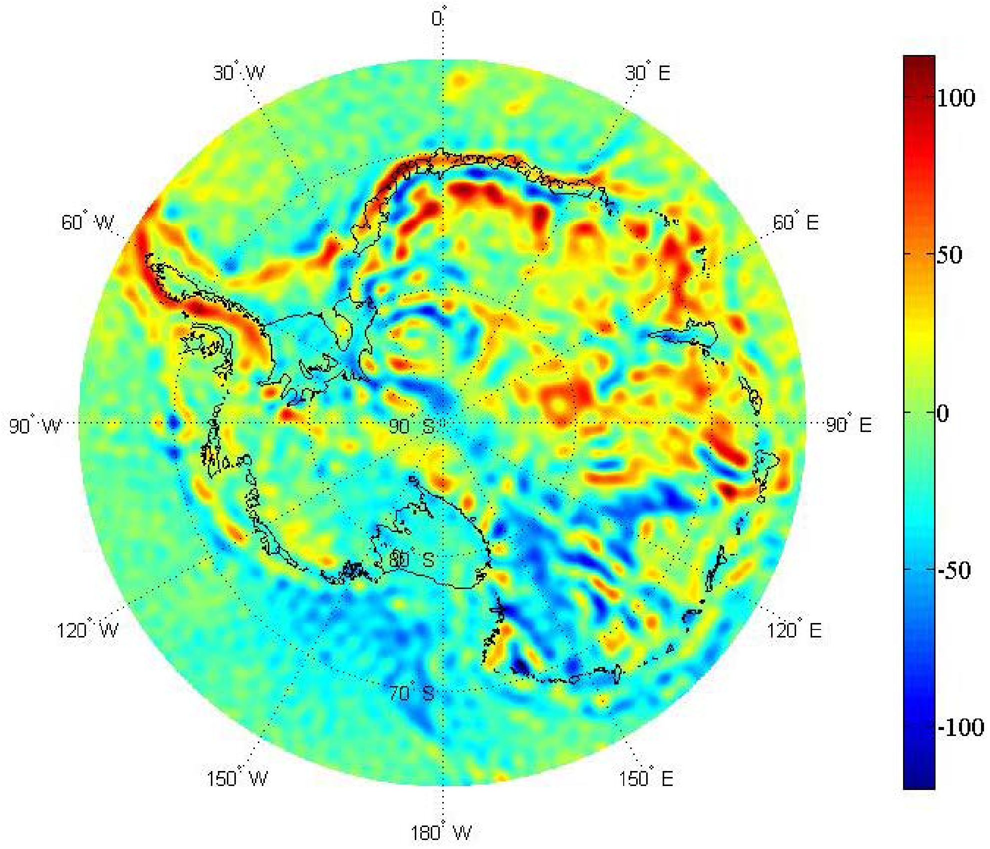
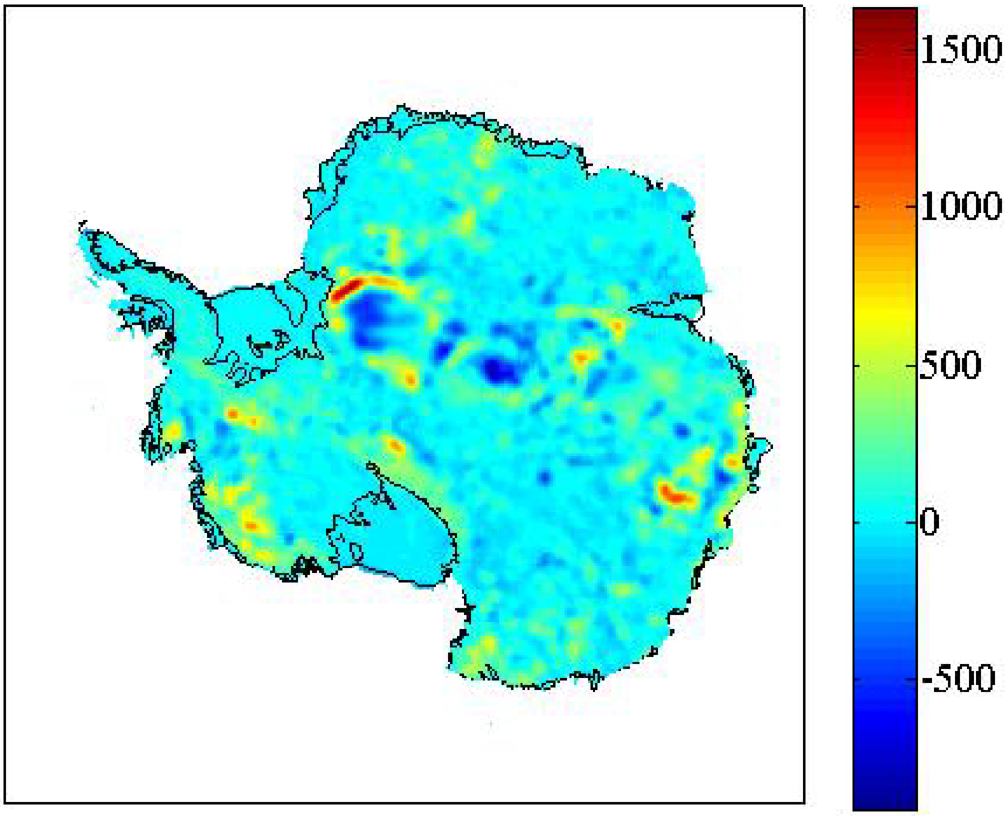


Figure 1. Free air anomalies in mgal from GOCE DIR5 solution.


1500
1000
500
0
-500

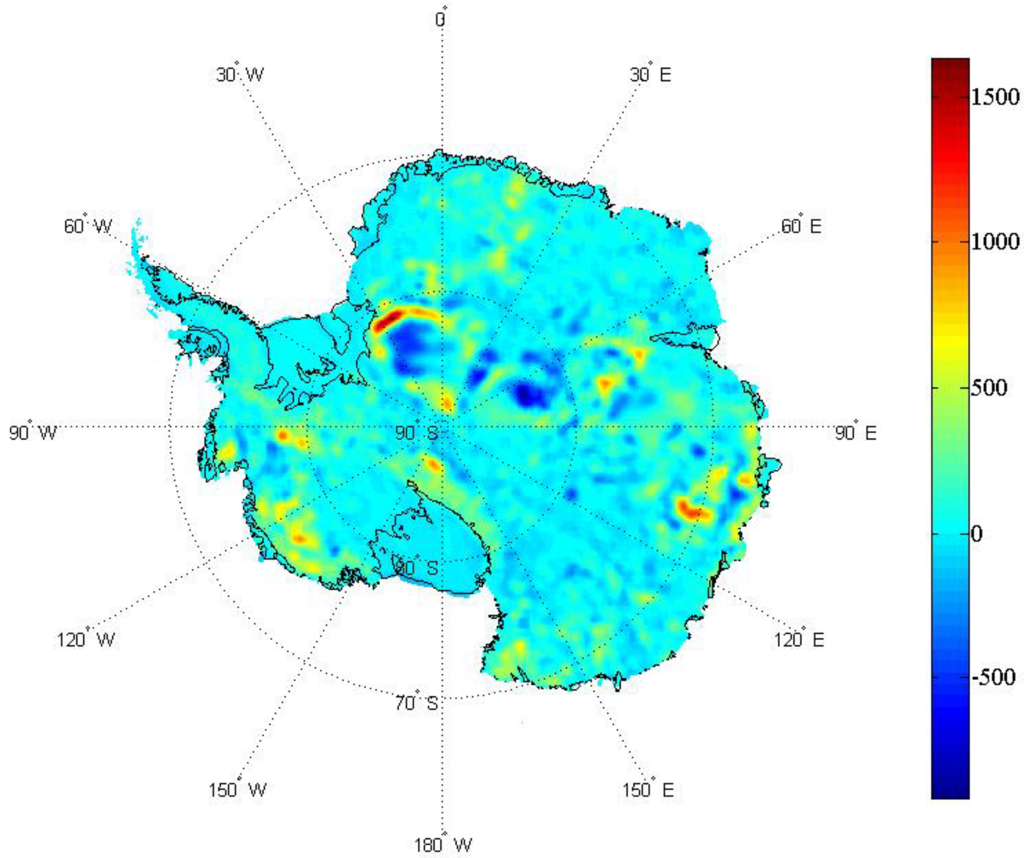
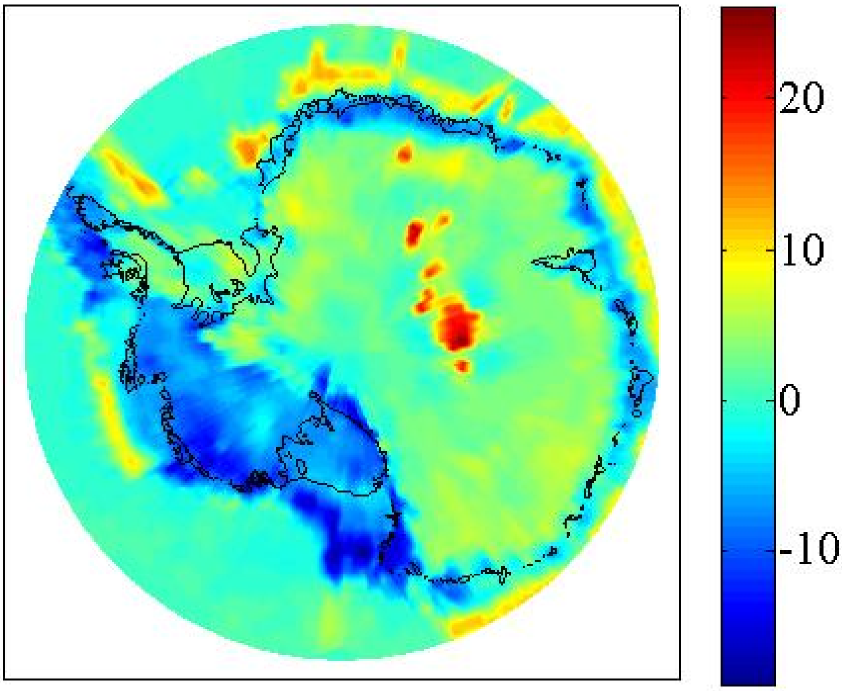


Figure 2. Difference between ice thickness from ~~BEDMAP2~~Bedmap2 and ~~BEDMAP1~~BEDMAP (max: 1628 m, min: -896 m, mean: 19 m). This difference is filtered to the maximum spatial resolution of GOCE (77 km) to represent the range of wavelengths that they are significant in our study.


20
10
0
-10

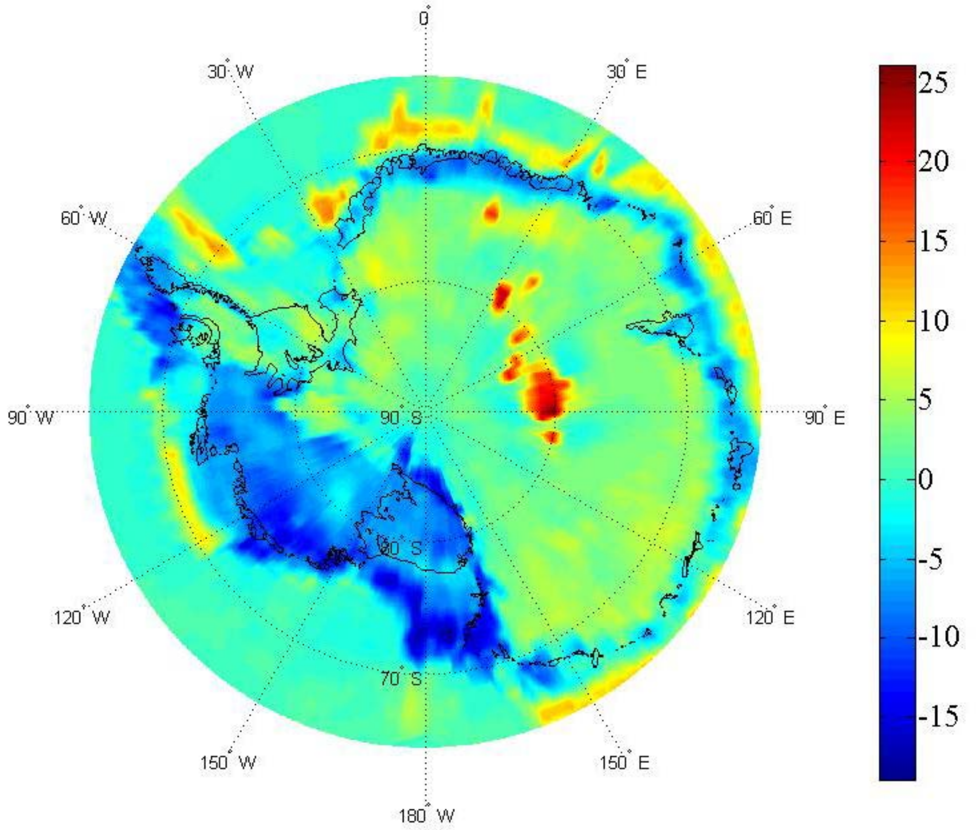


Figure 3. Difference between crustal models AN1 and CRUST 1.0 based from seismological data. Units are km.

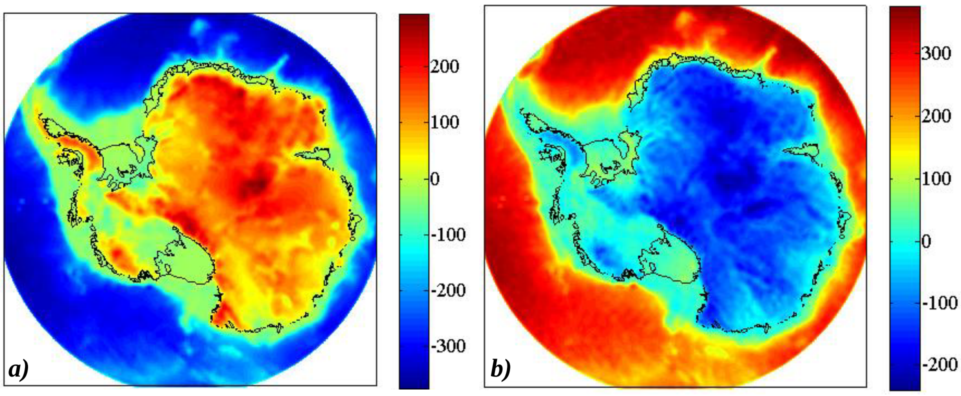


Figure 4.a) Gravitational terrain effect derived from ~~BEDMAP1~~BEDMAP ice thickness, sea and bedrock topography. Low pass filter of 77 km cut-off is applied. **b)** Bouguer anomalies estimated as the difference of GOCE observed free air anomalies and terrain effects. (in mGals)

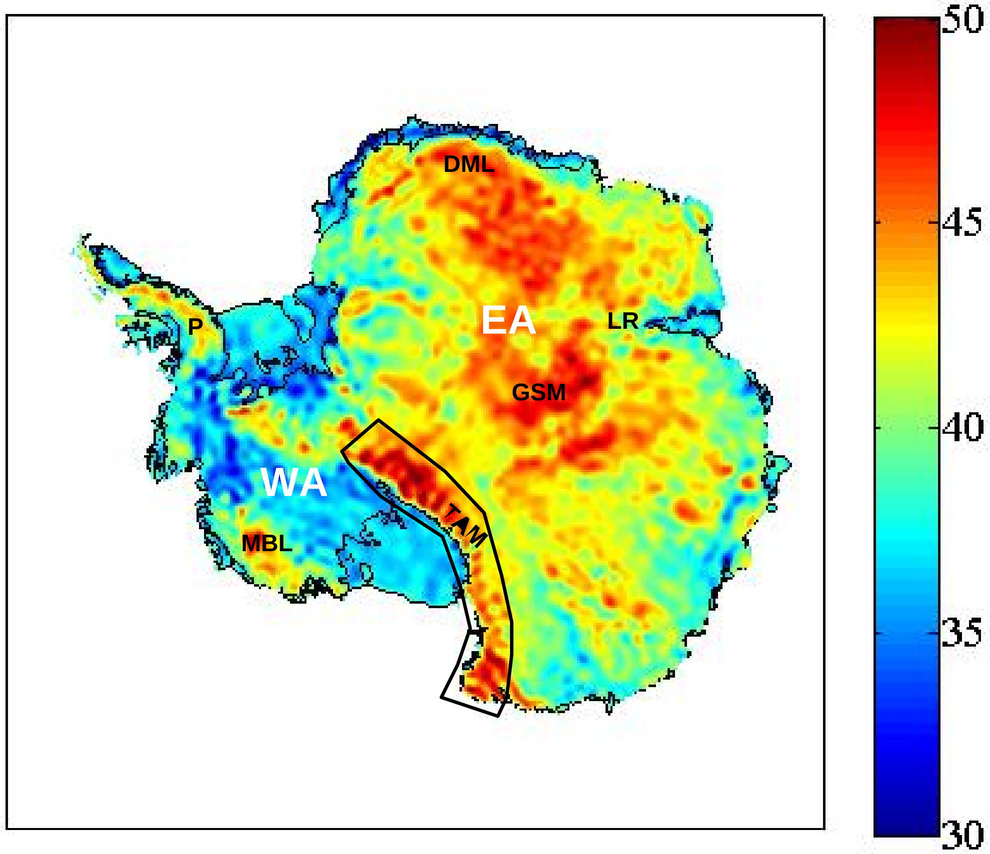
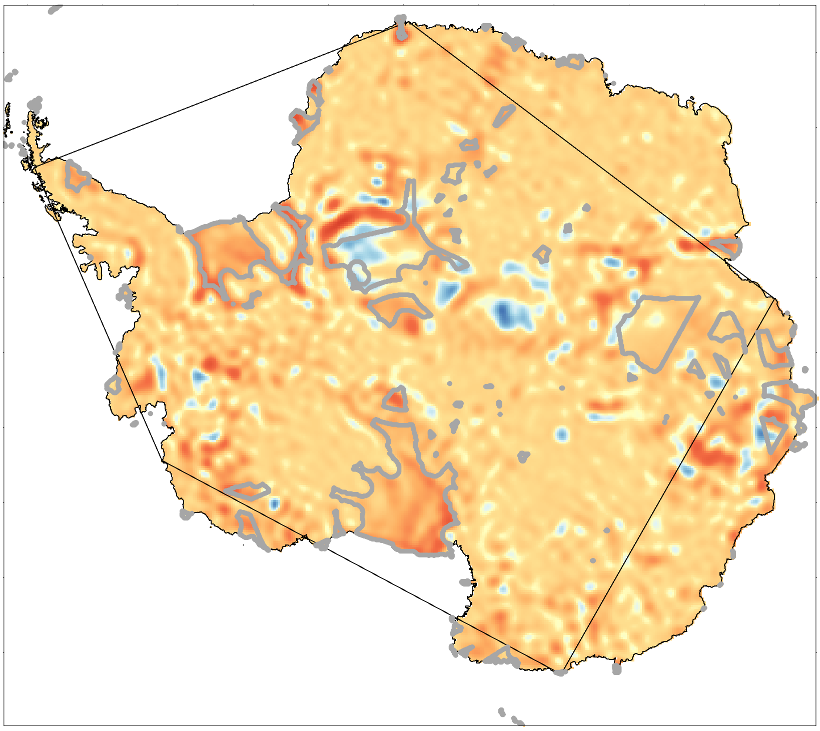


Figure 5. Estimation of crust thickness (in km) from GOCE gravity observations. Geographical locations mentioned in the text are: Dronning Maud Land (DML), Lambert Rift (LR), Gamburtsev Subglacial Mountains (GSM), TransAntarctic Mountains (TAM), Marie ~~Bird~~Byrd Land (MBL) and the Peninsula (P). The large TAM separate East Antarctica (EA) from West Antarctica (WA).



Formatted: Normal, Left

Formatted: List Paragraph, Centered

Formatted: Font: Bold

Formatted: Normal, Left

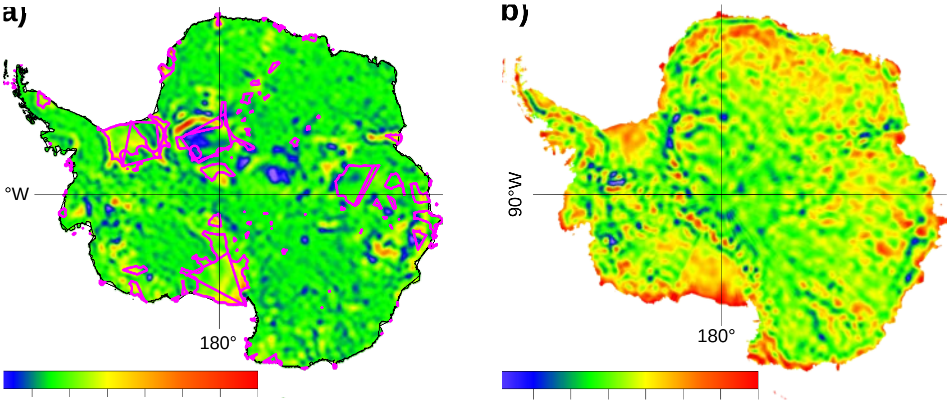
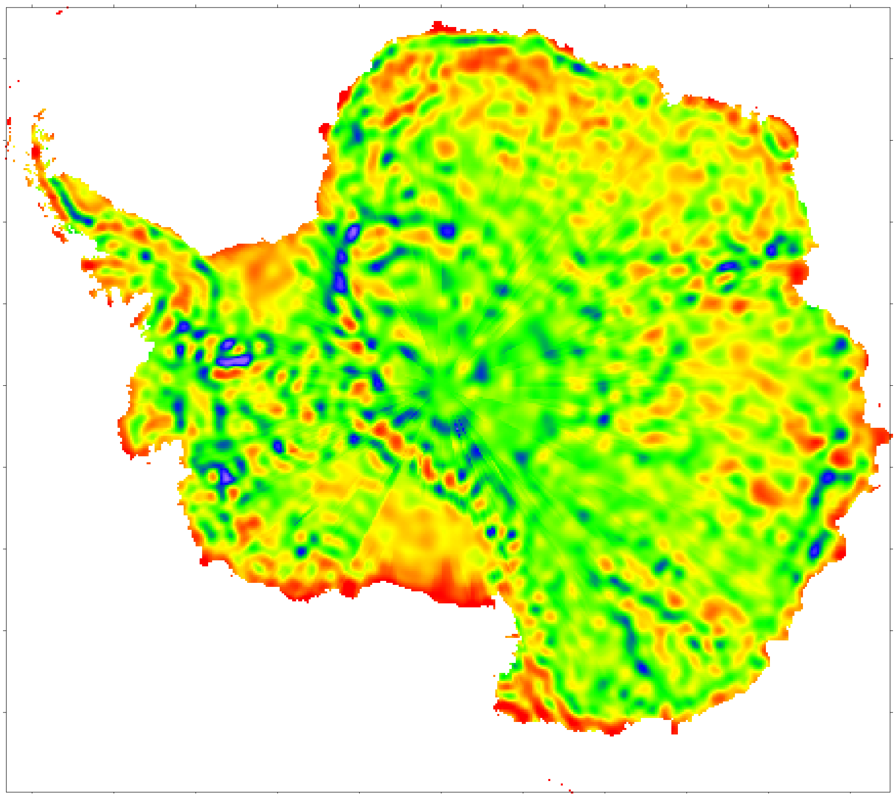


Figure 6. a) Differences between estimation of crust thickness: results using BEDMAP1BEDMAP minus results using BEDMAP2Bedmap2. The greypink line delimitates the zones where GOCE observations are used in BEDMAP2Bedmap2. Units are km.

Formatted: Left

Formatted: Font: Bold



~~**Figure 7.** Difference~~ **b)** Differences between the crust thickness computed from GOCE and the CRUST1.0 model. Units are km.

Formatted: Left

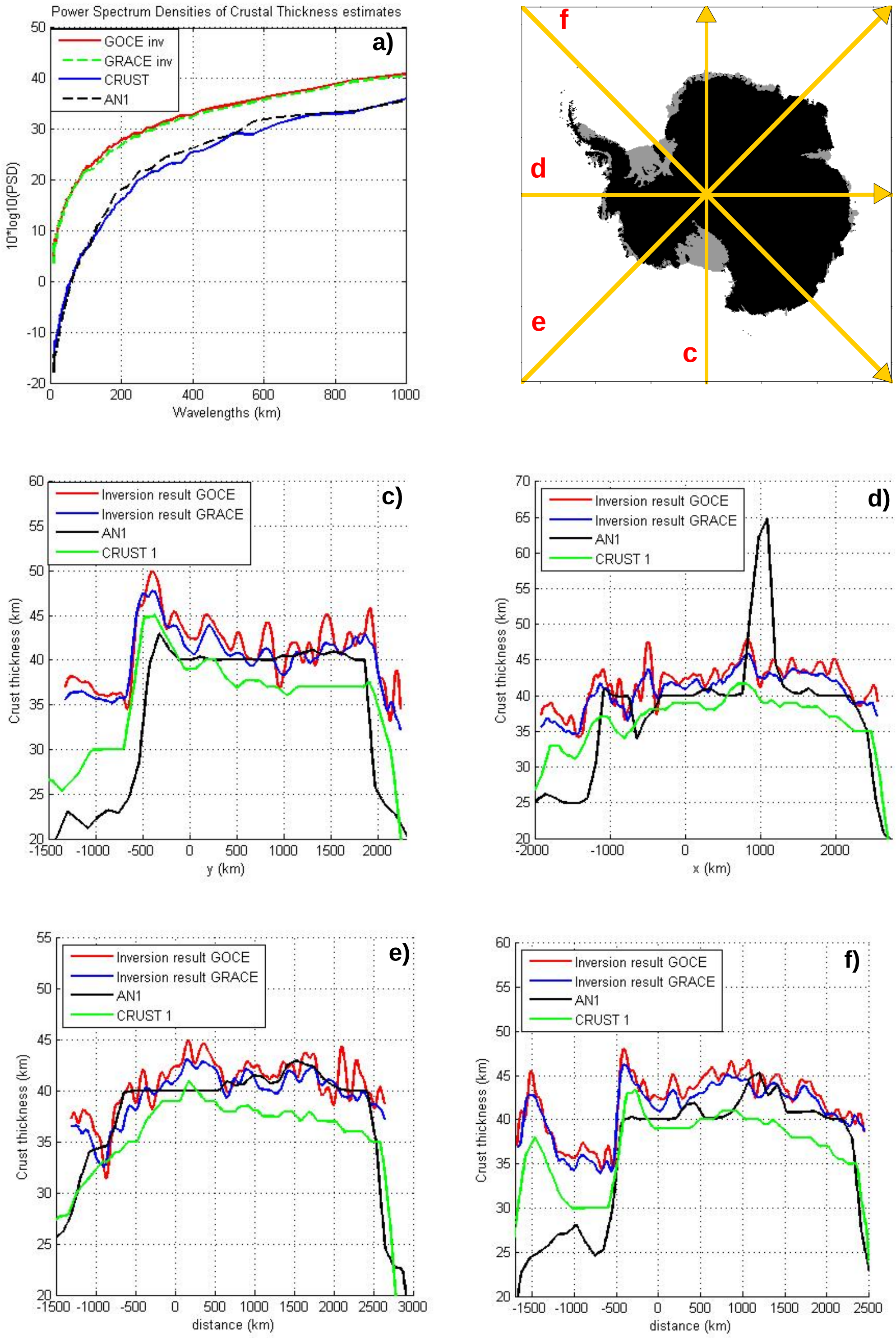
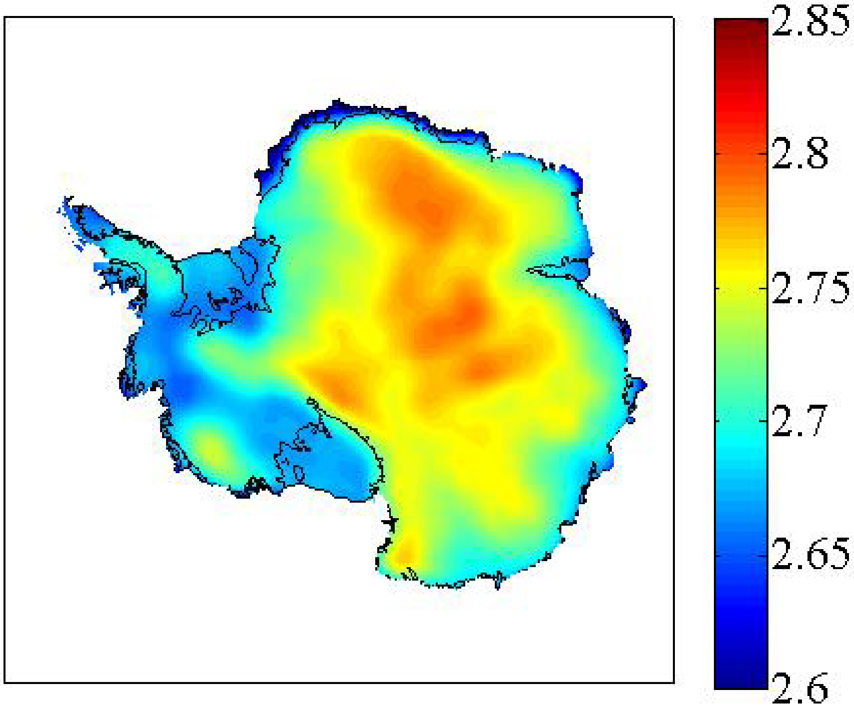


Figure 87. Spectral analysis crust thickness models (a), and their thickness variations over 4 profiles directions.shown with yellow lines in fig b. The Antarctica map is converted in a cartesian X-Y coordinate system. The profiles are c) parallel to Y, d) parallel to X, e) X=Y and f) X=-Y. The south pole is located at (0,0).


2.85
2.8
2.75
2.7
2.65
2.6

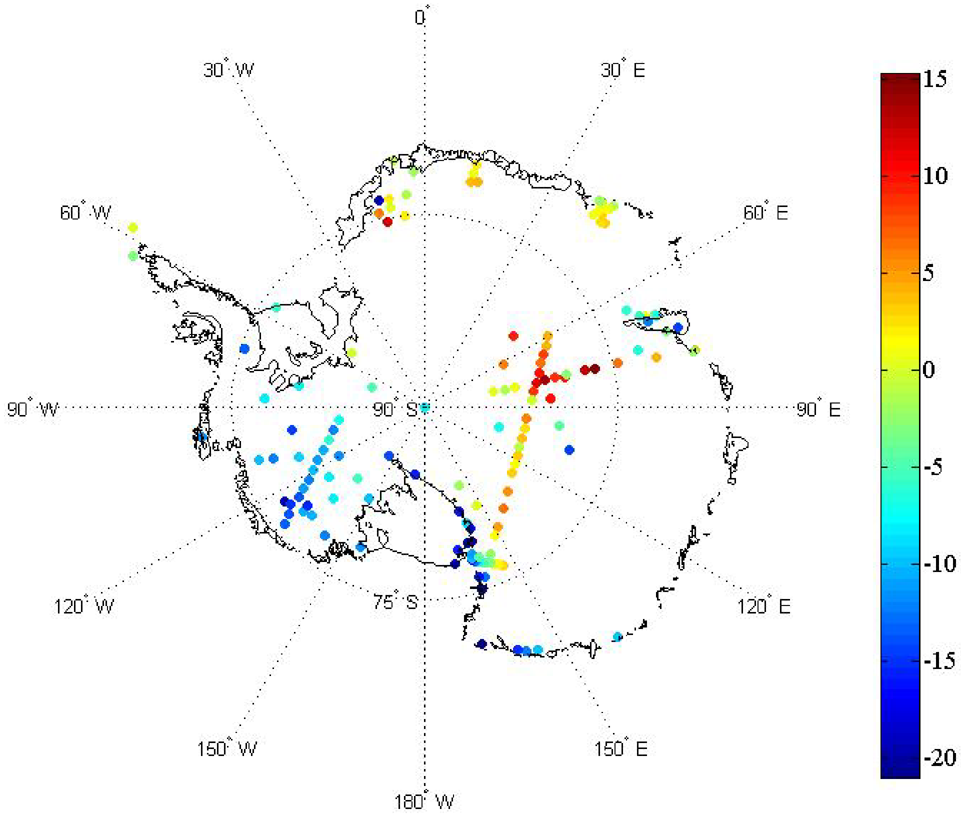


Figure 8. Differences between the compilation of receiver functions selected by An (An et al., 2015, Fourth culomn of Table S1) and the crustal thickness obtained in this study. Units are km.

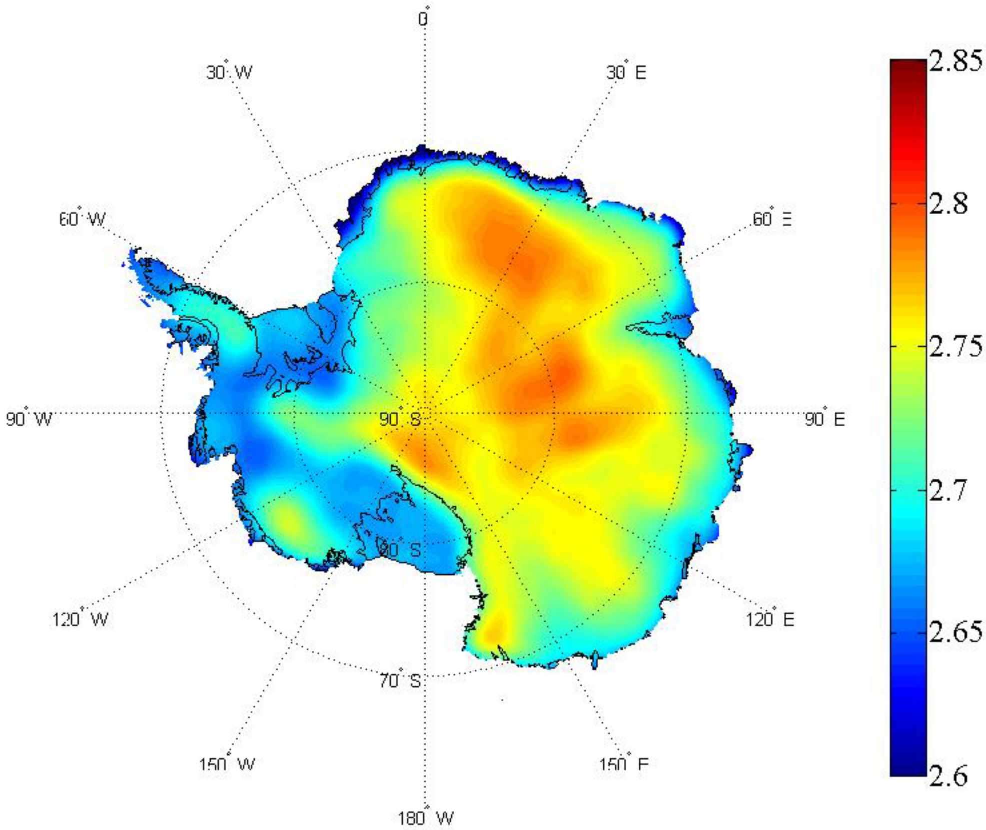


Figure 9. Density variations estimated from CRUST 1.0 crustal thickness variations.