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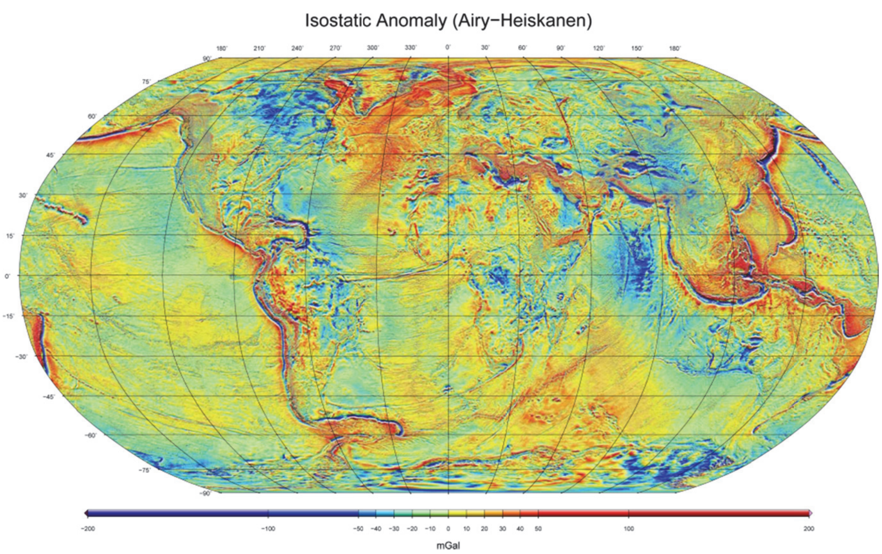
WORLD GRAVITY MAP

Scale 1 : 50 000 000

(First edition – 2012)



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World Gravity Map

Explanatory notes

The World Gravity Map (WGM) denotes a set of high-resolution gravity anomaly maps and digital grids computed at global scale from available reference Earth's gravity and elevation models. The Release 1.0 (2012) includes a set of three anomaly maps (surface free-air, complete Bouguer and isostatic anomalies) derived from the EGM2008 Geopotential model and the ETOPO1 Global Relief model. The WGM is the first set of global gravity anomaly maps that take into account a realistic Earth model and that consider the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps and ice shelves) (**fig.1**). Based on rigorous computations that are consistent with geodetic and geophysical definitions of gravity anomalies, WGM provides homogeneous information on the Earth's static gravity field at regional and global scales (also available in digital form) for various geophysical applications in education and research. Further releases are expected to include more surface data (field, marine or airborne surveys) to improve the short wavelengths of the gravity field (potential data providers are invited to contact BGI).

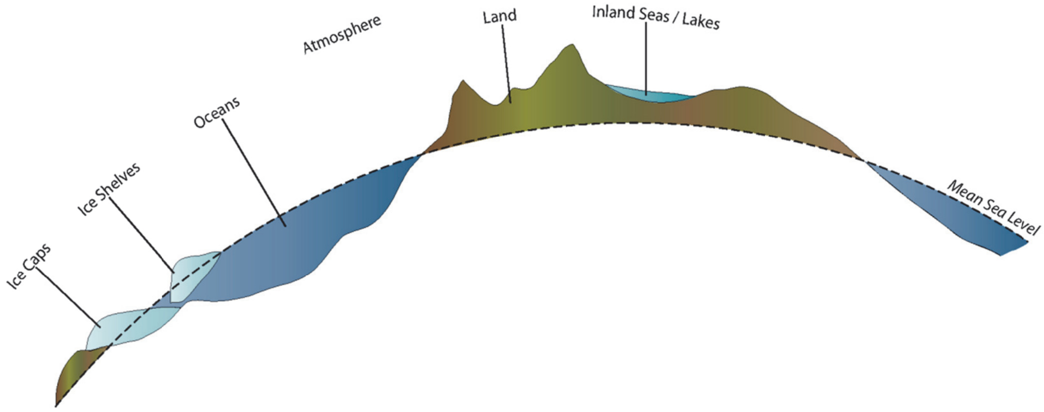


Fig. 1. *Surface masses taken into account in WGM Release 1.0 (2012) gravity anomaly computations*

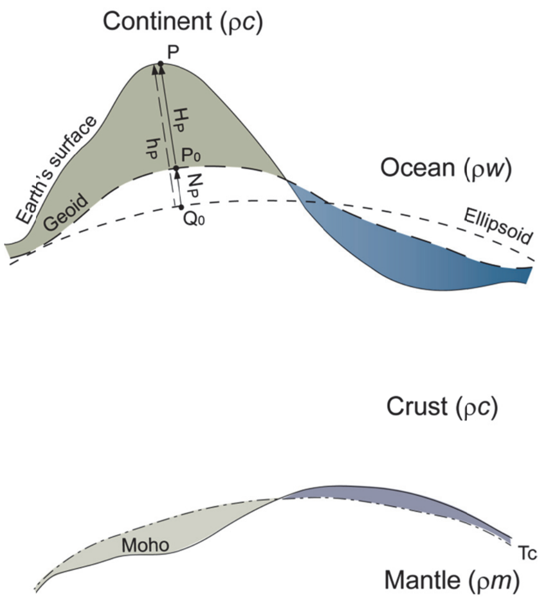
Definition of gravity anomalies

The "gravity anomaly" is defined as the difference between the gravitational acceleration (i.e. gravitation and rotation) caused by the Earth's masses and that generated by a reference mass distribution. Its study is of major importance in geodesy and geophysics and concerns a wide variety of applications in the Earth sciences. In geodesy, gravity anomalies are used to define the figure of the Earth, particularly the geoid surface which is defined as the equipotential surface that more closely represents mean sea level. In geophysics, gravity anomalies are used to investigate the mass-density distribution of the Earth's interior to provide constraints on the geological structures from subsurface, crustal to upper mantle depths. This approach led to the concept of "free-air", "Bouguer" and "isostatic" gravity anomalies described hereafter and used extensively for decades in geophysical interpretation. Recently, new formulations have been proposed to compute gravity anomalies based on both a realistic Earth model and rigorous geodetic definitions. More details on these modern views of anomaly computation can be found in Featherstone and Dentith (1997), Li and Götze (2001), Hackney and Featherstone (2003), Hinze et al. (2005), NGA (2008) and Kuhn et al. (2009).

The *Bouguer gravity anomaly* at a given point P (on the Earth's surface) is given by:

$$\Delta g_B(P) = g_{obs}(P) - g_{theor}(P) = g_{obs}(P) - \gamma_0(Q_0) + \delta g_{FC} - \delta g_{TOP} + \delta g_{Atm} \qquad (1)$$

where $g_{obs}(P)$ is the observed gravity at point P and $g_{theor}(P)$ is the theoretical gravity computed from the reference Earth model.



As shown in equation (1) and **fig. 2**, the theoretical gravity corresponding to point P can be derived from: the normal gravity $\gamma_0(Q_0)$ determined on the surface of the reference ellipsoid (Somigliana-Pizzetti formula), a height correction δg_{FC} (also called the free-air correction) accounting for the change in normal gravity from the reference ellipsoid to the point location using the orthometric height H_P, and a topographic correction δg_{TOP} accounting for the gravity attraction of the surface masses (topography and bathymetry for instance) above or below sea level. The topographic correction δg_{TOP}, also called the complete Bouguer correction in geophysical applications, aims to model and remove non-geological effects and is usually defined as the sum of two terms: the simple Bouguer correction (known as the Bullard B correction) and the terrain correction (known as the Bullard C correction), both of which account for the gravitational attraction produced at point P by, respectively, an infinite Bouguer plate or shell of constant thickness H_P and density ρ_c and by the irregularities of the topography/bathymetry residuals to the Bouguer plate/shell. Note that using h_P (instead of H_P) in the free-air and Bouguer corrections will result in the computation of gravity disturbances (instead of gravity anomalies). δg_{Atm} is an atmospheric correction term, given as a function of elevation with respect to sea level, accounting for the mass of the atmosphere.

Fig. 2.: *Schematic graph showing the main geodetic surfaces used in the computation of gravity anomalies. H_P is the orthometric height of P (normal to the geoid in P_0). h_P and N_P are the ellipsoid and geoid heights, respectively (normal to the ellipsoid in Q_0). The lower part illustrates the principle of mass compensation at the crust-mantle boundary used in the Airy-Heiskanen isostatic model.*

The resulting complete Bouguer anomaly thus reflects the disturbance between the observed gravity and that computed for a given reference Earth model at a same point P. It is also defined from the *free air anomaly* $\Delta g_{FA}(P)$ as:

$$\Delta g_B(P) = \Delta g_{FA}(P) - \delta g_{TOP} \qquad (2)$$

Global computation of gravity anomalies

In geophysical applications, the gravity anomalies are usually computed at local or regional scales and various approximations are applied to achieve computations in planar or spherical geometries. Here, the complete spherical Bouguer anomaly is determined over the whole Earth by computing in a single step the gravity contribution of all mentioned surface masses above or below the mean sea surface (**fig.1**). In the same way, the contribution of their compensation at the crustal-mantle boundary is also computed in spherical geometry on the base of isostatic equilibrium (Airy-Heiskanen model) to determine the corresponding isostatic anomaly. A spherical harmonic approach has been used to provide homogeneous and accurate global computations of gravity corrections and anomalies up to degree 10800 (1'x1' half-wavelength equivalent spatial resolution). To achieve this level of accuracy, new theoretical developments were required in order to handle spherical harmonics to ultra-high degrees (Balmino et al., 2011).

The spherical Bouguer gravity anomaly at a given point P of the Earth's surface is given by:

$$\Delta g_B(P) = \Delta g_{Surface\ free-air} - \delta g_{Surface\ masses} = g_{obs}(P) - \gamma(Q) - \delta g_{Surface\ masses} + \delta g_{Atm} \qquad (3)$$

where $g_{obs}(P)$ is the observed gravity at point P, $\gamma(Q)$ is the normal gravity computed at point Q on the *Telluroid* (the best analytical representation of the Earth's Surface) corresponding to P and $\delta g_{Surface\ masses}$ denotes the gravity attraction for all surface masses as described below. Note that the usual Bouguer plate effect is implicitly replaced here by the effect of a global spherical shell at each point P.

The term $\delta g_{Surface\ masses}$ produced by the surface masses below and above sea level was thus computed in spherical geometry at 1'x1' resolution using the ETOPO1 ice surface and bedrock models provided by the National Oceanic and Atmospheric Administration (NOAA) (Amante and Eakins, 2009) and taking into account the continents, oceans and the precise characteristics (boundaries and densities) of major lakes, inland seas, polar ice caps and shelves and land areas below sea level. The resulting global gravity effect computed from the spherical harmonic synthesis/analysis of the (orthometric) elevation data given in tables 1 and 2 is shown in **fig. 3**. As done for the surface masses, we also derived the spherical harmonic gravity coefficients for the compensation of all relief components for the Airy-Heiskanen isostatic model (see **fig. 2)** with a constant compensation depth *Tc* (here arbitrarily fixed to 30km). We thus produced global correction grids (1'x1') for both surface masses and isostatic effects computed at the Earth's surface to produce the final maps of complete spherical Bouguer and isostatic anomalies. To keep the information contained in the original data sets, all computations were made up to degree and order 10800.

The gravity information given in all gravity anomaly maps (Bouguer, isostatic and surface free-air) is derived from the EGM2008 geopotential model (Pavlis et al., 2008) / DTU10 gravity field (Andersen, 2010). The surface free-air gravity anomaly was computed at the Earth's surface in the context of Molodensky theory (Heiskanen and Moritz, 1967) and includes corrections for the mass of the atmosphere. All gravity anomaly maps and grids were computed at the Earth's surface (lower limit of the atmosphere) with a 1'x1' resolution. The reference density used for the Bouguer and isostatic anomaly maps is 2670 kg/m^3.

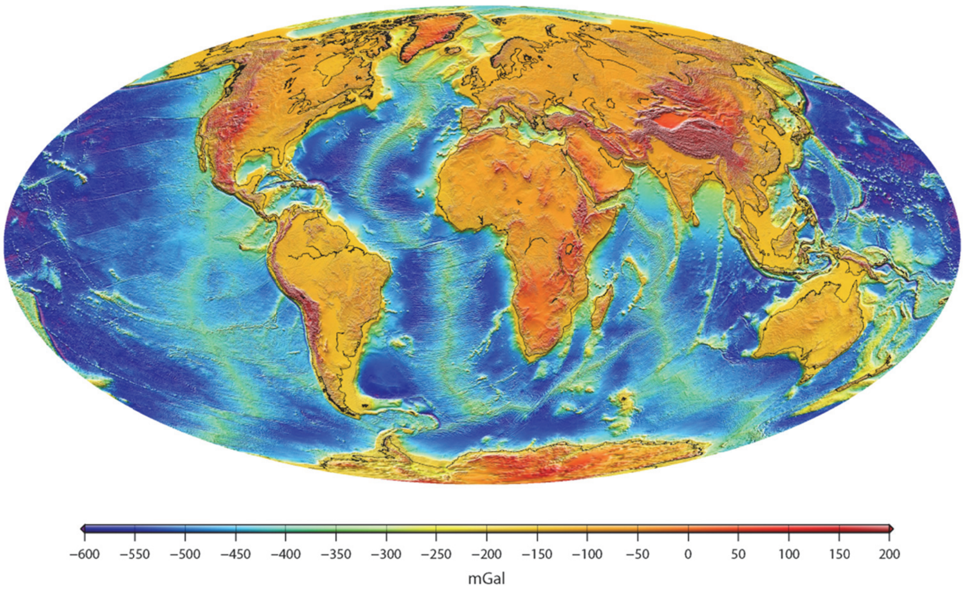


Fig. 3. *Spherical gravity attraction produced by surface masses considered from the ETOPO1 Global Relief model in the computation of Bouguer and isostatic anomalies. It corresponds to the gravity contribution (in mGal) of all land topography, ocean bathymetry, lakes, inland seas, ice caps and ice shelves (fig.1 and tables 1 and 2) computed in spherical geometry at the Earth's surface (base of the atmosphere). Densities used here are 2670 kg/m^3 (crust), 1027 kg/m^3 (ocean water), 1000 kg/m^3 (lake and inland sea water), 917 kg/m^3 (ice).*

Data sources

Gravity field data

The gravity information used in this release 1.0 is derived from the Earth Geopotential Model EGM2008 developed in spherical harmonics and released up to degree 2160 (with some terms up to degree and order 2190) by the National Geospatial-Intelligence Agency (NGA) (Pavlis et al., 2008). The EGM2008 model includes surface gravity measurements (from land, marine or airborne surveys), satellite altimetry and satellite gravimetry (GRACE mission) measurements. Updated information on the Arctic gravity field provided by the Technical University of Denmark (Andersen, 2010) and included in the DTU10 global gravity field model (1'x1' resolution) has been included (see referenced website for more details and technical specifications on EGM2008 and DTU10 gravity fields).

Elevation data

Elevation data (i.e. topography and bathymetry) is from the 1'x1' ETOPO1 Global Relief model. Ice caps are derived from the ice surface and bedrock ETOPO1 models (see Amante and Eakins, 2009 and referenced website for more details and technical specifications).

Lakes and inland seas

Lake features were extracted from the ILEC World Lake Database (see referenced website for more details and technical specifications). The lake boundaries were sampled through a polynomial interpolation of points from the SRTM Digital Elevation Model.

Land	Above sea level: all ; Below sea level: Chott Algeria-Tunisia, Quattara, Death Valley, Netherlands (part), Turfan	ETOPO1
Oceans	All	ETOPO1
Closed seas	Aral sea, Caspian sea, Dead sea	ETOPO1
Lakes	*See details in table 2*	ILEC, SRTM
Ice caps	Greenland, Antarctica	ETOPO1
Ice shelves	Ross, Ronne Filchner, Larsen and Amery	ETOPO1

***Table 1**: Sources of elevation data taken into account*

Africa	Nyasa (Malawi), Tanganyika, Victoria
Asia	Baikal, Balkach, Ladoga, Tiberiade*, Yssyk-Koul*
Europe	Constance*, Leman, Onego
North America	Bear lake*, Erie, Huron, Michigan, Ontario, Salton Sea*, Slaves*, Superior, Winnipeg
South America	Maracaibo*, Salto Grande, Titicaca
Oceania	Eyre

*Not in ILEC Data Base

***Table 2**: List of lakes taken into account*

Densities

Crustal rock density : 2670 kg/m^3
Mantle rock density : 3270 kg/m^3
Ocean water density : 1027 kg/m^3
Fresh water density : 1000 kg/m^3
Ice density : 917 kg/m^3

Map information

Coverage area : global (-180° to 180° ; -90° to 90°)
Mercator map projection
WGS84 ellipsoid
Equatorial scale : 1/50,000,000
North & South poles (60° to 90°): Polar stereographic projection

Geodetic Reference System (GRS80)

γ_e=9.7803267715 m.s^{-2}
γ_p =9.8321863685 m.s^{-2}
a=6378137 m
b=6356752.3141 m
e^2=0.00669438002290
f=0.00335281068118

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Websites

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http://www.ccgm.org : CGMW - Commission for the Geological Map of the World
http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008 : NGA - EGM 2008 Geopotential Model
http://www.space.dtu.dk/English/Research/Scientific_data_and_models : DTU National Space Institute - DTU10 Global marine gravity field
http://www.ngdc.noaa.gov/mgg/global : NOAA - ETOPO1 Global Relief model
http://wldb.ilec.or.jp : ILEC - World Lake Database

Citation for this map and corresponding digital products:

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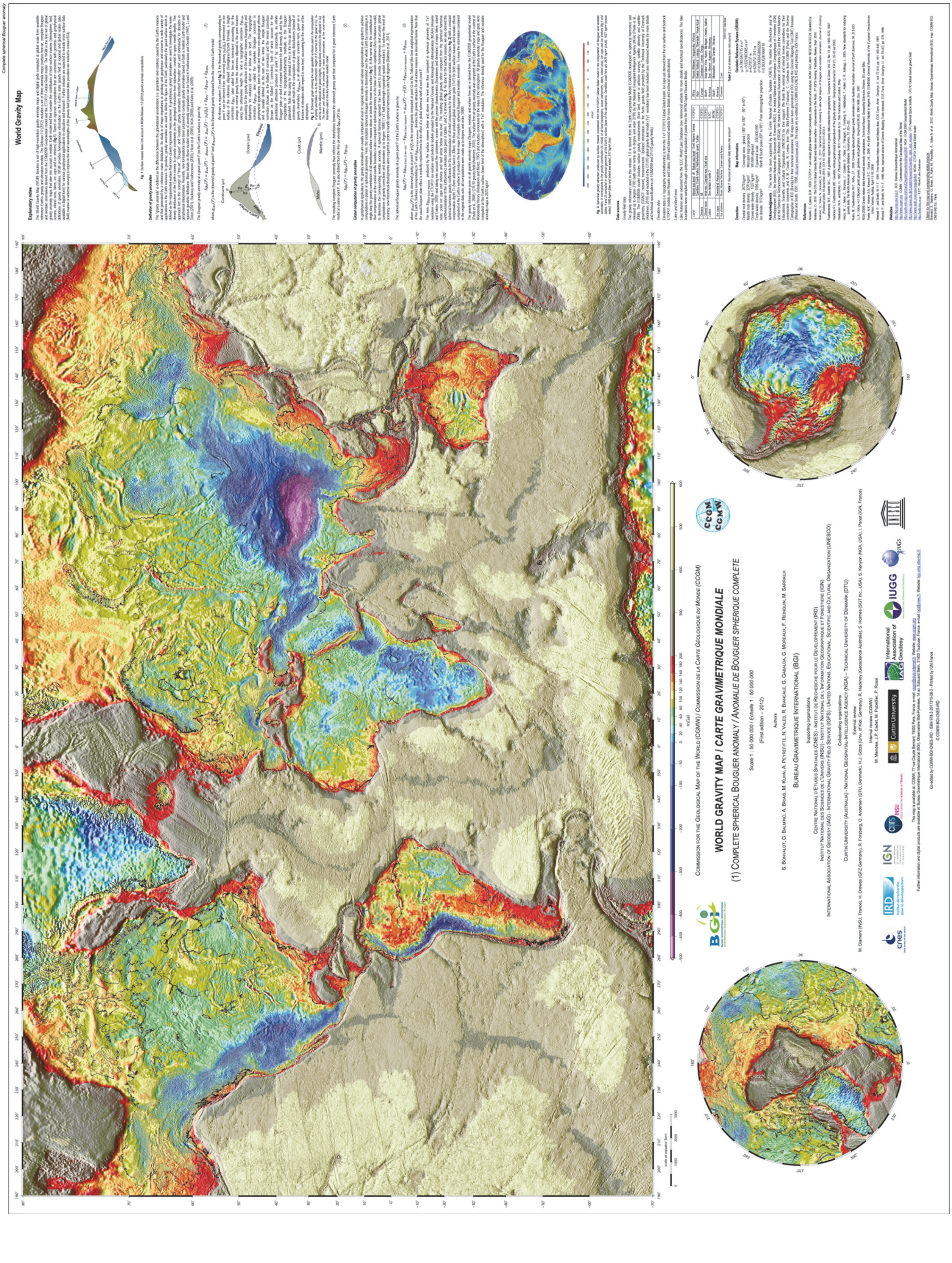
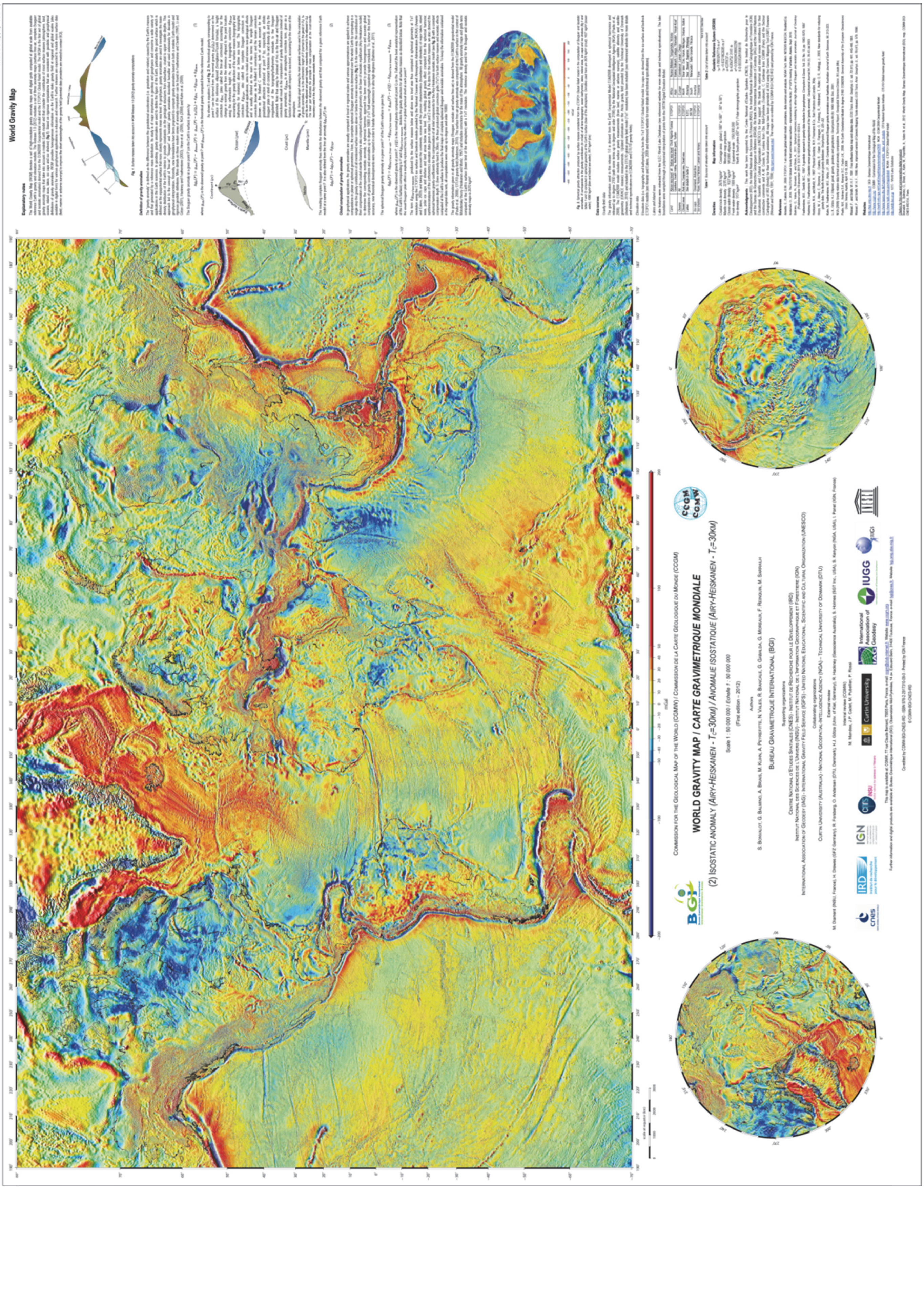
Citation for the theoretical background about this map and corresponding digital products:

Balmino, G., Vales, N., Bonvalot, S. and Briais, A., 2012. Spherical harmonic modeling to ultra-high degree of Bouguer and isostatic anomalies. *Journal of Geodesy*. July 2012, Volume 86, Issue 7, pp 499-520 , DOI 10.1007/s00190-011-0533-4.

MAP 1 / CARTE 1
COMPLETE SPHERICAL BOUGUER ANOMALY
ANOMALIE DE BOUGUER SPHERIQUE COMPLETE



MAP 2 / CARTE 2
ISOSTATIC ANOMALY (AIRY-HEISKANEN)
ANOMALIE ISOSTATIQUE (AIRY-HEISKANEN)



MAP 3 / CARTE 3

FREE-AIR ANOMALY ON THE EARTH'S SURFACE

ANOMALIE A L'AIR LIBRE SUR LA SURFACE TERRESTRE