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Recent changes of the Earth's core derived from satellite observations of magnetic and gravity fields

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To understand the dynamics of the Earth's fluid, iron-rich outer core, only indirect observations are available. The Earth's magnetic field, originating mainly within the core, and its temporal variations can be used to infer the fluid motion at the top of the core, on a decadal and subdecadal time-scale. Gravity variations resulting from changes in the mass distribution within the Earth may also occur on the same time-scales. Such variations include the signature of the flow inside the core, though they are largely dominated by the water cycle contributions. Our study is based on 8 y of high-resolution, high-accuracy magnetic and gravity satellite data, provided by the CHAMP and GRACE missions. From the newly derived geomagnetic models we have computed the core magnetic field, its temporal variations, and the core flow evolution. From the GRACE CNES/GRGS series of time variable geoid models, we have obtained interannual gravity models by using specifically designed postprocessing techniques. A correlation analysis between the magnetic and gravity series has demonstrated that the interannual changes in the second time derivative of the core magnetic field under a region from the Atlantic to Indian Ocean coincide in phase with changes in the gravity field. The order of magnitude of these changes and proposed correlation are plausible, compatible with a core origin; however, a complete theoretical model remains to be built. Our new results and their broad geophysical significance could be considered when planning new Earth observation space missions and devising more sophisticated Earth's interior models.

Earth's interior | core dynamics

Our planet is a very dynamic system, composed of the core and various layers, such as the mantle, lithosphere, oceans and atmosphere, up to near-Earth space. The fluid core (1), undergoing hydromagnetic motions, contributes to both the origin of the geomagnetic field (2, 3) and the spatial distribution of the Earth's mass (4, 5). Consequently, decadal and subdecadal time-scale processes occurring in the core produce signatures in the changes of the geomagnetic (6–8) and gravity (3, 4) fields. To date, short time-scale variations of core origin have only been evidenced in the magnetic field (9–11), and the gravity signals including the signature of the flow inside the core are largely dominated by the water cycle contribution (12). The question that now arises is to what extent core flow effects may be identified in other observables (than magnetic), such as gravity measurements; a core origin has been suggested as a possible cause for rapid geoid flattening variations (13, 14).

When either a surface observatory or a satellite takes a geomagnetic field measurement, this measure is the result of the superposition of many sources (15). The largest contribution generated by the dynamo action within the fluid, iron-rich core of the Earth is known as the core field, with a dominant dipolar component at the Earth's surface. Sizable contributions come from the static lithospheric field, and external field sources which originate in the ionosphere and magnetosphere.

Continuous satellite measurements made from 1999 to 2010 (16) have been used to build high-resolution models of the core magnetic field and its recent variations. Applying specifically devised methods, it is possible—globally—to improve from this model our knowledge of the core field and its variations, with a very high resolution in both space and time. The GRIMM models series (17, 18) are based on CHAMP satellite data and magnetic observatory hourly means. The GRIMM-3 model, covering the period from 2001 to 2010, describes the core field variations with periods shorter than one year. One of its special characteristics is the use of full vector satellite data at high latitudes and at all local times, for a better separation of different geomagnetic field sources: the ionospheric and magnetospheric field-aligned currents, the magnetized lithosphere, and the Earth's liquid core. The GRIMM-3 model describes the geomagnetic field using spherical harmonics up to degree $n = 30$ for the static field $n = 18$ for the first time derivative (secular variation, $\partial_t B$), and $n = 18$ for the second time derivative (secular acceleration, $\partial^2{}_t B$) (see *SI Text*). For the present study, the secular acceleration is considered up to $n = 8$. The evolution of the modeled secular acceleration at the Earth's surface is consistent with all available magnetic observations (from ground or near-Earth space), over the considered time interval (see Movie S1). Over the investigated period, very rapid changes in the trend of the secular variation of the geomagnetic field (geomagnetic jerks) appear at epochs 2003.7 and 2007.3 (19–21). These events provide evidence at the Earth's surface of sudden changes in the material flow at the top of the fluid outer core (9–11), and may have an impact on our understanding of the magneto-hydrodynamics of the Earth's core.

The very high-accuracy field and secular variation models allow us to compute large-scale flows (under different constraints; see *SI Text*) at the top of the core. Shown in Fig. 1 is the estimated flow at the core-mantle boundary, at epoch 2005. It is in a region below the Atlantic and Indian Oceans that the flow reaches the highest velocities. The short time-scale (decadal and subdecadal) secular variations of the magnetic field reveal a similar behavior of the flow, which might also be associated with a large-scale redistribution of core mass. This redistribution might induce in turn decadal and subdecadal changes of the gravity field. But other gravity variations, known and well described, are caused by mass redistributions within the climate system (con-

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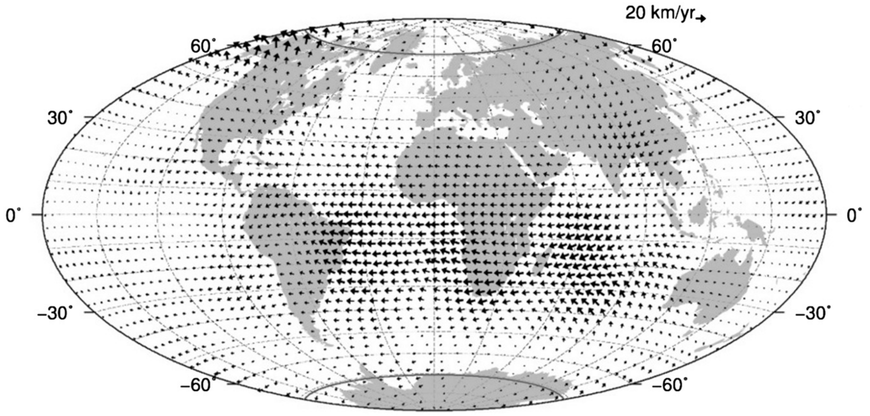

Fig. 1. Core flow at the top of the core derived from the radial core magnetic field component and its secular variation, as described by the GRIMM-3 model, for epoch 2005.

tinental hydrology, cryosphere, oceans, and atmosphere), both at the same time scales and at shorter periods (12, 22) (see *SI Text*). The impact of these external effects needs to be minimized prior to our analysis of core signals. For that, we have used the high-quality gravity field models obtained from the GRACE satellite gravity mission (16, 23). We have considered the CNES/GRGS (http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace) series of time variable geoid models (24) with a spatial resolution of 400 km, from which the effects of the solid Earth, oceanic and atmospheric tides, as well as of the oceanic and atmospheric mass variations are already removed using prior models (see *SI Text*). The resulting signal is then the sum of the effects of continental hydrology, the polar ice caps, improperly corrected atmospheric and oceanic contributions, and Earth's interior processes such as earthquakes, postglacial rebound, and core dynamics (25). To better isolate the core signal, we have estimated and removed the hydrological and aliases of oceanic tides contributions by fitting annual, semi-annual, and 161-d cycles (see Movie S2). In the following, these processed models are named "GRACE-A." Of course, some remaining climatic variability effects can still be present, especially in regions where the climate signal is large, and we return to it later on.

To date, no clear signals from the Earth's core had been seen in satellite gravity measurements. With our final models, we have systematically explored possible correlations between the temporal variations of the magnetic field and gravity anomalies, over the period from August 2002 to August 2010, with a 10-d sampling. We have reconstructed the corresponding magnetic and gravity time series on a global grid defined by 10° in geographic latitude and 20° in geographic longitude; this can be considered to be a well-distributed network of "virtual magnetic and gravity observatories" (VMGOs) located at the center of each cell. We

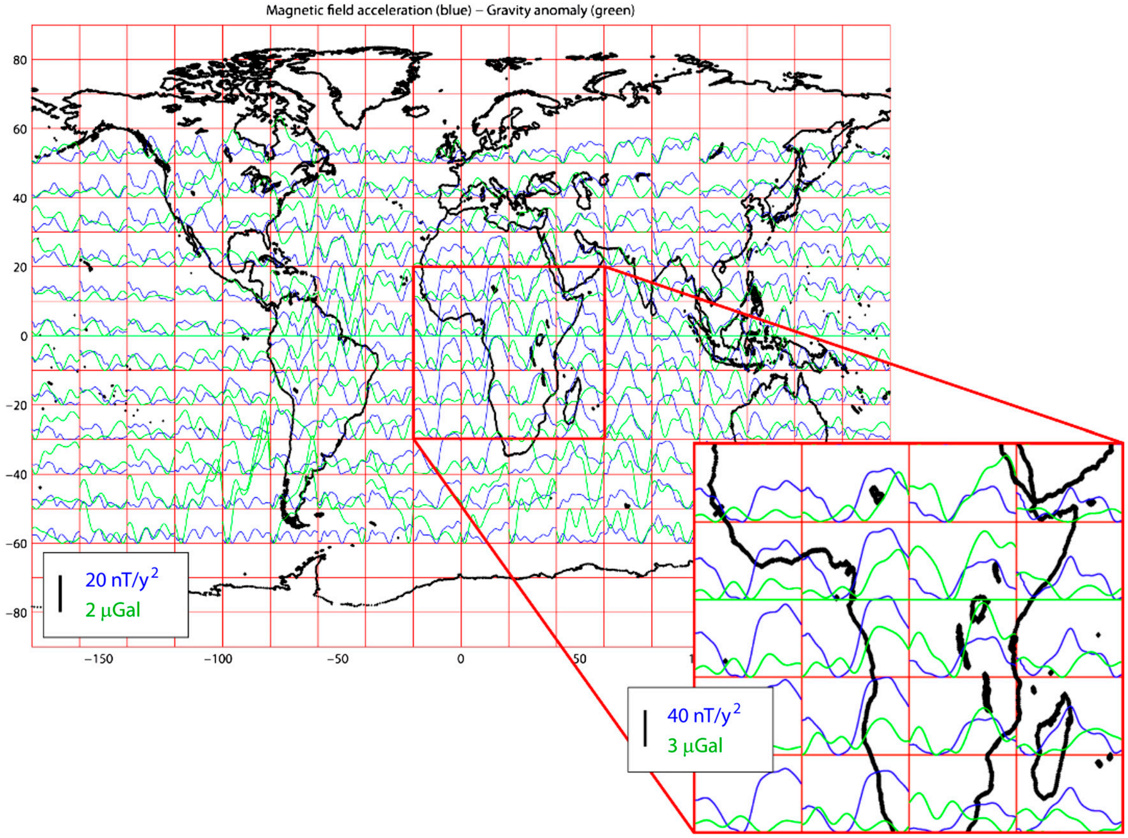

Fig. 2. Temporal variations for the secular acceleration of the vertical downward geomagnetic field component (blue) and the GRACE-A gravity anomalies (green), at each VMGO position. Each series starts in August 2002 and ends in August 2010 (top). A zoom over the LAB area is shown in the lower right panel, with different variation scales.

have noted that the secular acceleration of the vertical downward component (opposite in sign of the radial component) is the most outstandingly observed at VMGOs situated at low and middle latitudes. At higher latitudes, the signal/noise ratio is lower; for this reason, we have disregarded data at high latitudes (higher than 60°). Fig. 2 displays, in each cell, the 281 values of the secular acceleration of the vertical magnetic component and the 281 values of the gravity anomaly. It is intriguing to observe that both series show the same trends in their variations where the most important changes in the core flow occur, namely in the region beneath the Atlantic and Indian Oceans, to which we refer to as the Large African Box (LAB) area (Fig. 1).

To substantiate these results, we have computed, for each pair of magnetic and gravity values of the time series, their Pearson correlation coefficients, as well as their number of degrees of freedom, by estimating their decorrelation time (26, 27) (see *SI Text*). The significance of the correlation coefficients can be tested using the Student's *t* statistical test; we have determined for which pair of magnetic and gravity time-series the correlation is significant at the 95% level. Fig. 3*A* confirms our previous observation: the broadest continuous area of significant correlation is situated in the region of interest defined in Fig. 2.

To confirm these first results, we have further corrected the GRACE-A models from the effects of the geofluids at interannual time scales by considering the already published models for the oceanic (ECCO; http://www.ecco-group.org/) and continental hydrologic (GLDAS; http://disc.sci.gsfc.nasa.gov/services/grads-gds/gldas/index.shtml) contributions. The new obtained models are labeled "GRACE-B." Subtracting the modeled interannual geofluid contributions does not always reduce the variance in the GRACE-B models as compared to the GRACE-A ones. This reflects the difficulty in getting the very high precision needed on the climatic induced gravity variations in order to effectively enhance the core signals: there is indeed a trade-off between reducing the amplitude of the interannual water signal and increasing the error level of the GRACE-A fields by the geofluid model ones. Thereafter, we have repeated the above correlation estimates, and the results are shown in Fig. 3*B*. The correlation is robust over the largest part of the LAB area, disappearing only in the most Western part. Interestingly, the significant correlation disappears where the variance of the GRACE-B models is larger than that of the GRACE-A ones, in the Western part of the LAB area. In a larger Eastern part, the variance of the GRACE-B signal is smaller, and the correlation remains quite significant.

As core processes are large scale phenomena, it is necessary to investigate the common variability of the magnetic and gravity fields, globally. The singular value decomposition (SVD) technique allows us to retrieve this common variability for all the VMGOs, by decomposing the two sets of time series into a number of modes of common variation (28) (see *SI Text*). Each mode consists of a spatial pattern and a time series for each dataset. The SVD largest mode computed from both datasets is shown in Fig. 4. The results show that the anomaly observed between the Atlantic and Indian Oceans is part of a larger scale magnetic and mass distribution fluctuation. These distributions only coincide over the LAB area, where we can also observe fast core flows (Fig. 1). The associated time series show a slow oscillation at the subdecadal time-scale, consistent with the suddenness of geomagnetic jerks (10, 11).

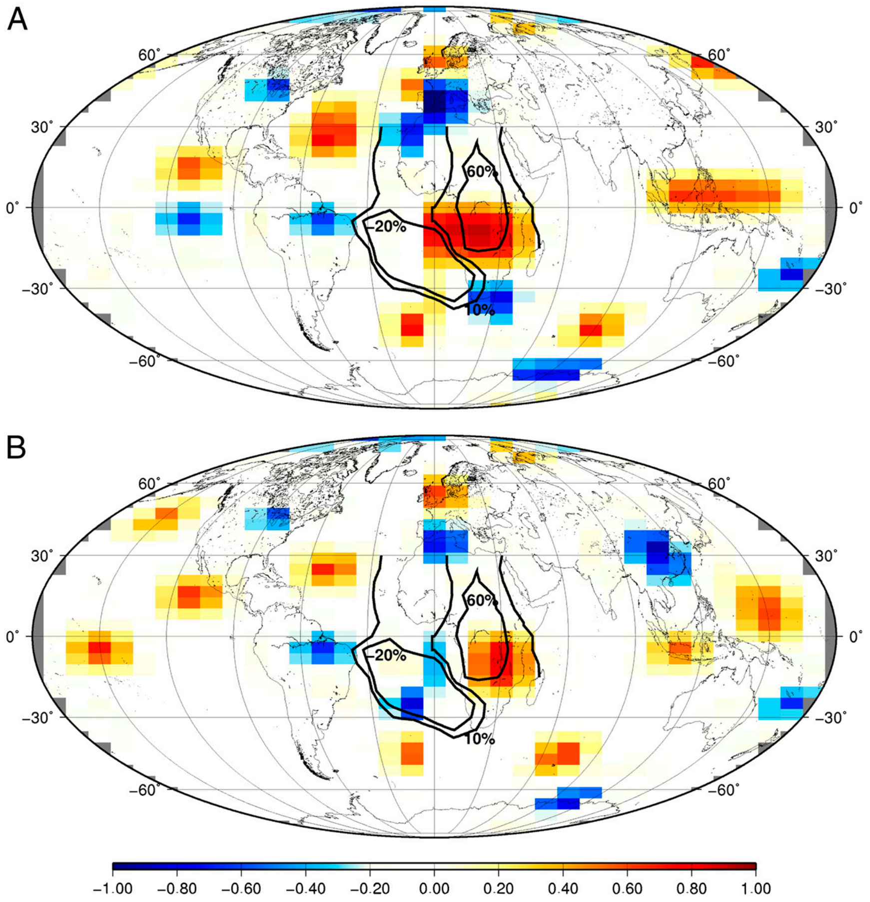

Fig. 3. Correlation between the GRACE-A (*A*) or GRACE-B (*B*) gravity anomaly series and the secular acceleration of the vertical downward geomagnetic field component. Black solid lines delimit areas where the variance of the GRACE-B models changes by the indicated values as compared to the GRACE-A. The open 10% contour line is drawn only around the LAB area. All correlation values that are not significant at the 95% level have been set to zero (white blocks).

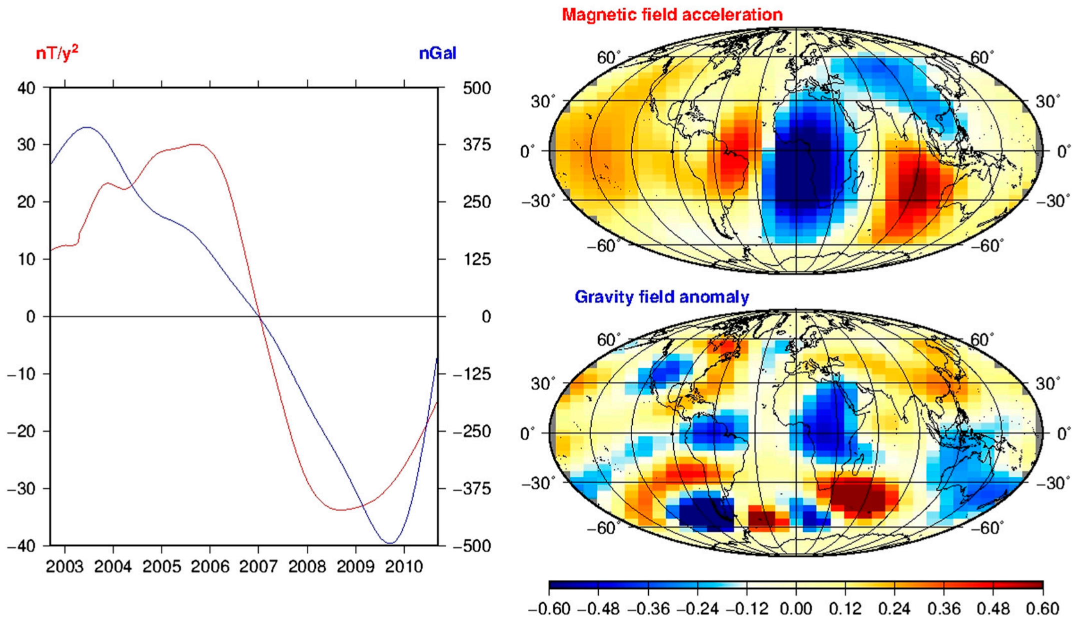

Fig. 4. Results of the singular value decomposition (SVD) for both time series. The left-side panel shows the temporal behavior of the two series: secular acceleration of the vertical downward geomagnetic field component (red) and gravity (blue). The right-side panels show the spatial pattern for the geomagnetic (top) and gravity (bottom) data.

Our study calls for a physical interpretation of the pointed correlations; i.e., a physical link between time variations of the magnetic field originating in the core and Earth's gravity variations. The standard view of the outer layers of the core is that liquid iron cannot support density heterogeneity large enough to generate a measurable gravity signal at the Earth's surface. Nevertheless, a density heterogeneity ρ_1 is linked with the flow at the top of the core whose velocity $\boldsymbol{U}$ can be estimated from the secular variation of the core magnetic field, considering a geostrophic equilibrium between the pressure gradient and the Coriolis forces (see Fig. 1 and *SI Text*); this density heterogeneity ρ_1 presents a time variability similar to those of the velocity field $\boldsymbol{U}$. Values of the magnetic secular variation up to some hundreds of nT/yr are associated with this flow.

The correlation observed between the time variations of the magnetic acceleration and gravity fields in the LAB region (see Figs. 2 and 4) leads to think that both may be generated by the flow $\boldsymbol{U}$. The LAB region—where an exceptionally strong decrease of the intensity of the core field is observed [some 10% over the last three decades (29)]—is indeed characterized by a strong westward flow at the core surface (see Fig. 1), creating a strong secular variation as a result of the advection of the non-axial dipolar part of the main field (in this case it is tangentially geostrophic; see *SI Text*).

The flow $\boldsymbol{U}$ can contribute to the gravity field variations in two ways. First, by advection of the density heterogeneity ρ_1 and corresponding mass transfer; if the top layers of the core are not stratified, ρ_1 is of the order of $10^{-9}\ \rho_0$, ρ_0 being the bulk density of these layers (approximately $10^4\ \mathrm{kg\,m^{-3}}$), and no significant effect could be expected. If, as proposed by ref. (30), the layers are stably stratified, ρ_1 can have much larger value (31); e.g., $10^{-5}\ \rho_0$. In such a case, values of the gravity anomaly Δg of the needed order of magnitude could be reached, although hardly; the radial length scale δ of the motion is reduced by the stratification. Temporal variations of $\partial_t \Delta g$ would in this case be correlated with the secular variation $\partial_t B_r$, or Δg and secular acceleration $\partial^2{}_t B_r$, as observed, in the case of harmonic variations. Another mechanism is rather efficient: the dynamic overpressure (associated with the flow $\boldsymbol{U}$) of the order of 10^3 Pa, deforms—feebly, but significantly—the overlaying elastic mantle, generating a gravity anomaly which can be computed through a Love number formalism (32). Our estimates show that, considering for example a degree 4 harmonic, an effect of the order of hundred of nanoGals at the Earth's surface can be reached; but in this case, Δg and secular variation $\partial_t B_r$ should correlate.

So we must say that, at this moment, we have no satisfactory explanation of the observed correlation between Δg and secular acceleration. Further investigation is needed; for example, we have not considered thermal and chemical diffusion, neither the phenomena taking place at the core-mantle boundary, at the contact between solid silicates and liquid iron. Building a complete magneto-hydrodynamic and gravito-elastic model is beyond the aim of this observation-based paper.

In this study, we propose that time variable signatures in the gravity field, generated by core processes, exist. Our results point towards a signature of the core contribution to the gravity field consistent with that which is observed in the geomagnetic field. The detected gravity changes produced by the core flow are small, but above the threshold of detectability in the high-precision GRACE measurements, and they are consistent with former theoretical estimates (4, 5).

The results presented here are highly encouraging to look for new information about the dynamics of the Earth's core via high-resolution, high-accuracy gravity data. For this, further GRACE-like quality observations (33) are required, over decadal timescales, together with the forthcoming Swarm magnetic satellite data (34). Such geopotential field observations will provide unprecedented insight into the month-to-month and year-to-year changes that are occurring deep within the Earth. Moreover, these results may impact on other disciplines, because rapid changes in the Earth's core influence vital parts of our environment, such as modifications of the South Atlantic Anomaly, with consequences on navigation or radio communications. The proposed analysis techniques can be applied to other areas of research, because a "virtual observatory" network can be developed for any parameter varying in time and space, and characterizing any planet.

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