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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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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. 3A 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. 3B. 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).

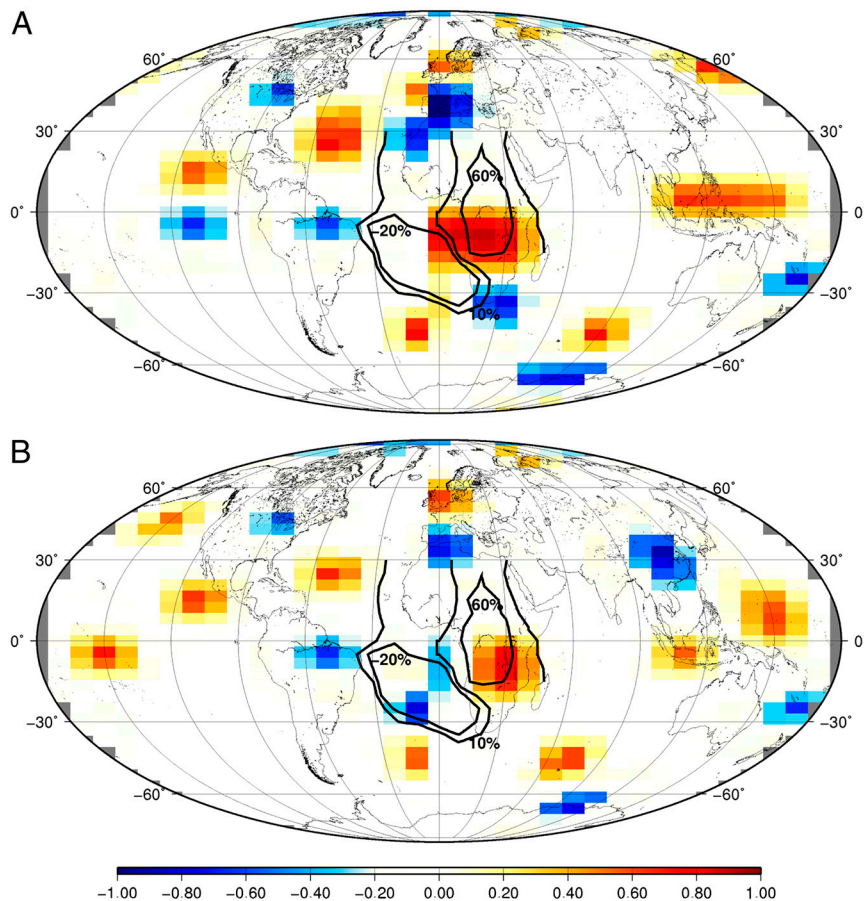


Fig. 3. Correlation between the GRACE-A (A) or GRACE-B (B) gravity anomaly series and the secular acceleration of the vertical downward geomagnetic field component. Black solid lines delimit areas where the variance of the GRACE-B models changes by the indicated values as compared to the GRACE-A. The 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).

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