Earth Rotation, Excitation, Core

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Definition

Earth Rotation, Excitation, Core. Temporal variations in the amplitude and orientation of the rotation vector of the solid Earth, which comprises the mantle and crust, excited by processes originating in the Earth's core.

Introduction

The Earth's magnetic field is generated and maintained by convective flows in the electrically conducting fluid outer core (FOC). Interactions between these flows and the mantle at the core-mantle boundary (CMB) and the solid inner core (SIC) at the inner core boundary (ICB) lead to transfers of angular momentum between the FOC, SIC and mantle. Within each of these three interior regions, a change in angular momentum entrains a change in the rotation vector. Observations of Earth rotation are made at the Earth's surface in a reference frame fixed to the crust. The latter is rotating with the mantle as a single body, so Earth rotation variations refer then to variations in mantle rotation. Thus, through torques between the mantle and core, convective core flows entrain changes in Earth rotation.

Variations in the rate of rotation are typically reported as changes in the period of rotation, or changes in the length of day (LOD), whereas changes in the direction of the rotation vector with respect to geographic coordinates are referred to as polar motion (see Earth Rotation, Theory). Since core flows are time-dependent, varying on time scales of milliseconds to millions of years, in principle they generate changes in LOD and polar motion at all timescales. However, they are difficult to detect at annual and shorter timescales because they are masked by larger variations excited by processes the fluid envelope at the surface (see Earth Rotation, Excitation, Atmospheric; Oceanic; Tidal). Core flows are responsible for a decadal variation and a 5.9 yr periodic change in LOD. Core flows have also been linked to millennial fluctuations in LOD. In contrast, a clear contribution from core flows to the observed polar motion has never been unequivocally demonstrated. A brief mathematical formulation of the interior angular momentum balance between the mantle, FOC and SIC is presented below, followed by a review of the contribution of core flows in exciting changes in LOD and polar motion.

Mathematical formulation

The equations describing the evolution of the angular momentum vectors ($\mathbf{H_m}$, $\mathbf{H_f}$, $\mathbf{H_s}$), and thus the rotation vectors ($\mathbf{\Omega}$, $\mathbf{\Omega_f}$, $\mathbf{\Omega_s}$) of the mantle, FOC and SIC, respectively, are (see Earth Rotation, Theory)

$$\frac{d}{dt}\mathbf{H_m} + \mathbf{\Omega} \times \mathbf{H_m} = \mathbf{\Gamma_{cmb}} + \mathbf{\Gamma_g}\,, \tag{1}$$

$$\frac{d}{dt}\mathbf{H_f} + \mathbf{\Omega} \times \mathbf{H_f} = -\mathbf{\Gamma_{cmb}} + \mathbf{\Gamma_{icb}}\,, \tag{2}$$

$$\frac{d}{dt}\mathbf{H_s} + \mathbf{\Omega} \times \mathbf{H_s} = \mathbf{\Gamma_{icb}} - \mathbf{\Gamma_g}\,. \tag{3}$$

These equations are written in a reference frame tied to the rotation of the mantle $\mathbf{\Omega}$. $\mathbf{\Gamma_{cmb}}$ and $\mathbf{\Gamma_{icb}}$ denote the torques from all surface forces exerted by the FOC on the mantle and SIC, respectively. $\mathbf{\Gamma_g}$ denote the gravitational torque by the SIC on the mantle, produced for instance by a differential rotation between the two. The angular momentum vector of each region can be further decomposed as

$$\mathbf{H_m} = \mathbf{I_m} \cdot \mathbf{\Omega}\,, \tag{4}$$

$$\mathbf{H_f} = \mathbf{h_f} + \mathbf{I_f} \cdot \mathbf{\Omega_f}\,, \tag{5}$$

$$\mathbf{H_s} = \mathbf{I_s} \cdot \mathbf{\Omega_s}\,, \tag{6}$$

where ($\mathbf{I_m}$, $\mathbf{I_f}$, $\mathbf{I_s}$) are the moment of inertia tensors of each region and $\mathbf{h_f}$ is the angular momentum carried by flows within the fluid core which depart from the rotationally rigid component associated with $\mathbf{\Omega_f}$. Note that we have assumed here for simplicity that no equivalent $\mathbf{h_m}$ and $\mathbf{h_s}$ exist in the mantle and SIC. A change in LOD corresponds to a change in the amplitude of $\mathbf{\Omega}$, whereas a polar motion reflects a change in the direction of $\mathbf{\Omega}$ with respect to the mantle frame.

Core flows can lead to temporal variations in $\mathbf{\Omega}$ (in Eq. 1) either through a torque at the CMB ($\mathbf{\Gamma_{cmb}}$), or via a torque on the inner core at the ICB ($\mathbf{\Gamma_{icb}}$) that entrains a differential rotation of the inner core and a subsequent gravitational torque on the mantle ($\mathbf{\Gamma_g}$). Additionally, core flows exert a non-uniform pressure on the CMB, leading to a deformation of the mantle, and thus a change in $\mathbf{\Omega}$ in response to a change in $\mathbf{I_m}$.

The sum of Eqs. (1-3) gives zero on the right-hand side, expressing conservation of angular momentum in the absence of an external torque,

$$\frac{d}{dt}\mathbf{H_m} + \frac{d}{dt}\mathbf{H_f} + \frac{d}{dt}\mathbf{H_s} + \mathbf{\Omega} \times (\mathbf{H_m} + \mathbf{H_f} + \mathbf{H_s}) = \mathbf{0}\,. \tag{7}$$

Changes in $\mathbf{\Omega}$ caused by core flows can thus be inferred through two different methods: the torque approach, which requires an evaluation of the total torque in Eq. (1) acting on the mantle; or the angular momentum approach, which consists in predicting the expected change in $\mathbf{\Omega}$ in Eq. (7) on the basis of $\mathbf{h_f}$, $\mathbf{\Omega_f}$ and $\mathbf{\Omega_s}$ deduced or reconstructed from observation, irrespective of the nature of the core-mantle torque.

Length of day variations

Fluctuations in LOD taking place over a few decades were first suggested by Newcomb (1882) and later confirmed by Glauert (1915), who interpreted these falsely to be caused by changes in the Earth's moment of inertia. We now know that they result instead primarily from an exchange of angular momentum between the core and the mantle, a suggestion that was argued on quantitative grounds first by Munk and Revelle (1952) but not formally demonstrated until the work of Jault et al. (1988).

The observed LOD variations (ΔLOD) over the past 50 years, after correcting for atmospheric and oceanic contributions and removing a tidal breaking trend, are shown in Fig. 1. The signal contains decadal fluctuations of approximately 3 milliseconds (ms) in amplitude and a periodic 5.9 yr oscillation of 0.12 ms (Holme and de Viron, 2013). The demonstration that the decadal LOD changes are caused by core flows was pioneered by Jault et al. (1988) and has been verified in a number of studies since. Time variations in flows at the top of Earth's core can be reconstructed form observed magnetic field variations (Holme, 2015). These flows contain zonal accelerations of cylindrical surfaces, depicted on Fig. 2b, which are expected on dynamical grounds. Since these cylindrical flows carry angular momentum, a prediction of the LOD change can be reconstructed on the basis of Eq. (7). The predicted ΔLOD matches well the observed decadal ΔLOD over the past century (Fig. 2a). A similar exercise can be carried for the 5.9 yr periodic oscillation, with equal success (Gillet et al., 2010).

The zonal flows that carry angular momentum at 5.9 yr are believed to be Alfvén waves: zonal oscillations of the cylindrical surfaces depicted in Fig. 2b sustained by the magnetic tension between them (Gillet et al., 2010). The nature of the zonal flows tied to the decadal ΔLOD is less certain. They may consist in zonal accelerations driven by continuously fluctuating magnetic torques acting on cylinders as a by-product of the continuous distortion of the magnetic field by convective flows (More and Dumberry, 2018). Alternately, or additionally, they may also involve Magnetic-Archemedian-Coriolis (MAC) waves in a stratified layer at the top of the core (Buffett, 2014).

Although the role of the core in the 5.9 yr and decadal changes in LOD is firmly established on the basis of the global angular momentum budget, the mechanism by which this angular momentum exchange occurs (the torque on the right-hand side of Eq. 1) remains an open

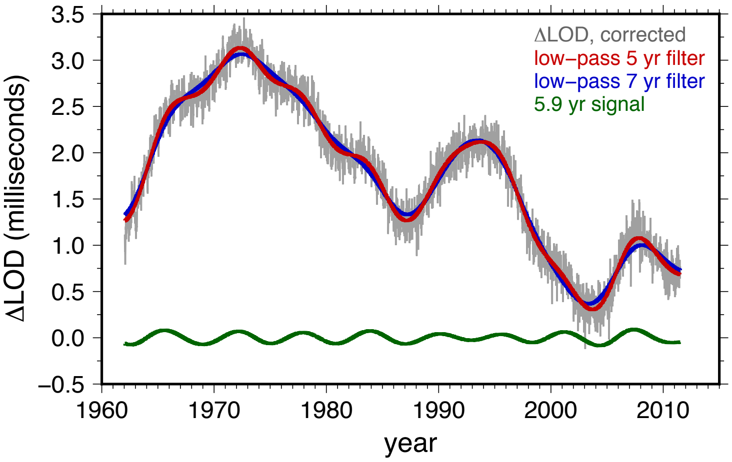

Figure 1: Observed ΔLOD (grey) after subtracting the contribution from the oceans and atmosphere and removing a linear trend (from Holme and de Viron, 2013). The red (blue) curve shows the LOD signal after applying a third order low-pass Butterworth filter with a cutoff period of 5 yr (7 yr). The difference between these two filtered signals highlights the presence of a 5.9 yr periodic signal (green).

question. Viscous friction at the CMB can be discounted on account of the very small viscosity of the fluid core. Electromagnetic coupling (Rochester, 1960), which can be efficient if the lower mantle is a reasonably good electrical conductor, and topographic coupling (Hide, 1969), in which flows push on "bumps" at the CMB, both contribute to $\mathbf{\Gamma_{cmb}}$ in Eq. (1) and have been investigated in many studies (see Gross, 2015; Buffett, 2015, for reviews). Another possibility involves the SIC: through electromagnetic coupling at the ICB, core flows should entrain fluctuations in the SIC rotation rate. Gravitational coupling between density anomalies in the SIC and those within the mantle can then entrain LOD changes through $\mathbf{\Gamma_g}$ in Eq. (1) (Buffett, 1996). Which of these torque (topographic, electromagnetic, gravitational), or combination, is responsible for the observed decadal and 5.9 yr ΔLOD remains the subject of active research.

Changes in LOD at millennial timescales can be reconstructed from ancient eclipse observations (Stephenson et al., 2016). The millennial ΔLOD are shown in Fig. 3a, after the

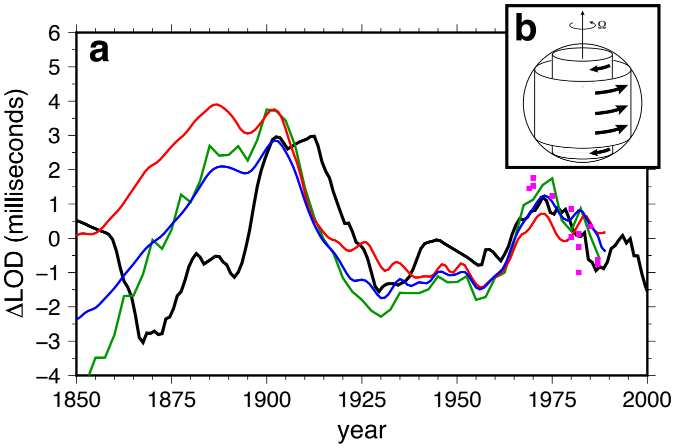

Figure 2: a: Observed ΔLOD (black line) versus predictions reconstructed under the assumption that the equatorially symmetric, axisymmetric zonal flows extend rigidly inside the core (cylindrical flows, shown in b). The core flow models shown are: purple squares = Jault et al. (1988); blue = Jackson (1997); green = Hide et al. (2000); red = Pais and Hulot (2000).

contributions of tidal breaking and glacial isostatic adjustment (GIA) have been removed (Mitrovica et al., 2015). The remaining LOD signal includes fluctuations of a few ms in amplitude, though the precise details are far more uncertain than the ±3 ms error suggested by Stephenson et al. (2016). A prediction of LOD changes computed from core flows that are compatible with millennial magnetic field changes (Dumberry and Bloxham, 2006) is also shown in Fig. 3a. The zonal flow geometry used for this prediction is different than at decadal timescales, involving a shear in the direction of the rotation axis (Fig. 3b). The fit to the observed ΔLOD is clearly not as good as at decadal timescales. This is not surprising given the much larger uncertainty of both the LOD observation and magnetic field reconstruction, in addition to the ambiguity in computing core angular momentum changes on the basis of non-rigid zonal flows. Nevertheless, this prediction demonstrates that core flow fluctuations over the past few millennia can (and should) generate changes in LOD of a few ms in amplitude, so they are most likely responsible for the observed changes. In further support to the role of core flows, with a geometry resembling that of Fig. 3b, the reconstruction of Dumberry and Bloxham (2006) suggests a core which is on the whole rotating faster today compared to its average rate during the past 3000 yr. This is visible on Fig. 3a: the predicted LOD (red line) is longer today than its millennial average. The accumulated clock error from this effect is consistent with the part unaccounted for by tidal breaking and GIA that is required to match the eclipse record (Mitrovica et al., 2015).

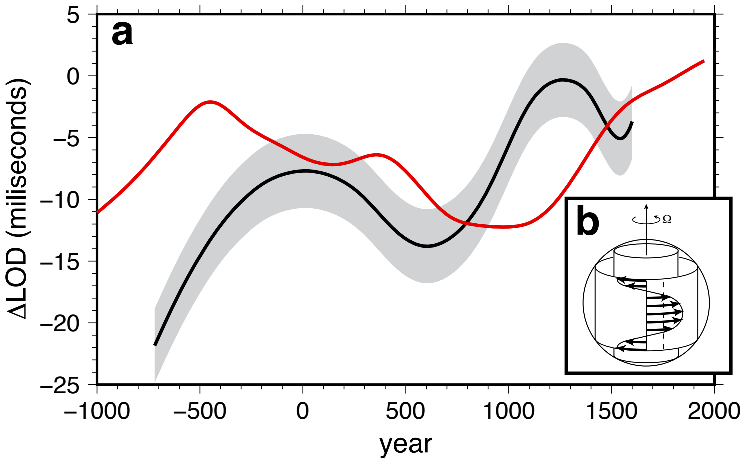

Figure 3: a: Observed ΔLOD (black line, ±3 ms error in grey) based on eclipse observations (from Stephenson et al., 2016) after removing the tidal and GIA contributions, and prediction (red line) from Dumberry and Bloxham (2006) reconstructed from time-dependent non-rigid zonal core flows (geometry shown in b).

Polar motion

The observed polar motion over the past one hundred years is dominated by the 14-month Chandler wobble and an annual variation, both excited by surface processes. There is also a secular drift caused by a combination of changes in the mantle moment of inertia from GIA, ice sheet melting, and mantle convection (see Gross, 2015). Once these are removed, an irregular decadal fluctuations in polar motion with a magnitude of roughly 15 to 30 milliarcseconds (mas) appears to be present. This decadal polar motion was first identified by Markowitz (1960) and, for this reason, is often referred to as the Markowitz wobble.

Because observations prior to 1976 were based on optical astrometry measurements, known to be corrupted by systematic errors, the authenticity of this decadal polar motion signal has often been challenged. However, the more reliable, higher precision space geodetic measurements after 1976 confirmed the existence of a decadal polar motion, though with a smaller amplitude of approximately 15 mas.

Based on gravity measurements by the GRACE twin satellites, Adhikari and Ivins (2016) have shown that mass fluctuations at the Earth's surface from terrestrial water storage and glaciers can explain the decadal-like polar motion between 2003 and 2015. By conjecture, the same explanation should then hold for the earlier fluctuations. Nevertheless, given that the decadal changes in LOD are caused by core flows, many studies have sought to determine whether they can also act as a source of decadal polar motion. Calculations of the electromagnetic and topographic torque at the CMB do indeed suggest that core flows can generate a decadal polar motion, though not one large enough to explain the observations (Greff-Lefftz and Legros, 1995; Hide et al., 1996; Hulot et al., 1996). Core flows can also generate a torque on the inner core leading to a tilt of its oblate figure with respect to the mantle. Because of the density jump at the ICB, this entrains a change in the moment of inertia of the core (Greiner-Mai and Barthelmes, 2001; Dumberry and Bloxham, 2002) and a polar motion. However, the required tilt is too large to be generated by electromagnetic (Mound, 2005) or gravitational coupling (Dumberry, 2008). Thus, although core flows unmistakably entrain a decadal polar motion, its amplitude may contribute at best only a fraction of the observed polar motion.

Summary

Turbulent, convective flows in Earth's fluid core lead to torques on the mantle and inner core. These result in an exchange of angular momentum between the fluid core, inner core and mantle and an associated change in Earth's rotation vector. Changes in LOD at decadal timescales and for a periodic signal of 5.9 yr can be shown to be induced by core flows on the basis of the angular momentum budget. Core flows also contribute to millennial fluctuations in LOD. However, the precise nature of the torque responsible for the core-mantle angular momentum transfer at all these timescales remains an open question. To this day, there is still no convincing demonstration that any part of the observed polar motion is the product of core-mantle interactions.

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Cross references

Earth Rotation, Theory

Earth Rotation, Excitation, Atmospheric

Earth Rotation, Excitation, Oceanic

Earth Rotation, Excitation, Tidal

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