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Physics of the Earth and Planetary Interiors 154 (2006) 113–147

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

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Axial and equatorial rotations of the Earth's cores associated with the Quaternary ice age

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Received 8 October 2004; received in revised form 18 August 2005; accepted 31 August 2005

Abstract

The differential axial and equatorial rotations of both cores associated with the Quaternary glacial cycles were evaluated based on a realistic earth model in density and elastic structures. The rheological model is composed of compressible Maxwell viscoelastic mantle, inviscid outer core and incompressible Maxwell viscoelastic inner core. The present study is, however, preliminary because I assume a rigid rotation for the fluid outer core. In models with no frictional torques at the boundaries of the outer core, the maximum magnitude of the predicted axial rotations of the outer and inner cores amounts to $\sim 2^\circ\ \text{year}^{-1}$ and $\sim 1^\circ\ \text{year}^{-1}$, respectively, but that for the secular equatorial rotations of both cores is $\sim 0.0001^\circ$ at most. However, oscillating parts with a period of ~225 years are predicted in the equatorial rotations for both cores. Then, I evaluated the differential rotations by adopting a time-dependent electromagnetic (EM) torque as a possible coupling mechanism at the core-mantle boundary (CMB) and inner core boundary (ICB). In a realistic radial magnetic field at the CMB estimated from surface magnetic field, the axial and equatorial rotations couple through frictional torques at the CMB, although these rotations decouple for dipole magnetic field model. The differential rotations were evaluated for conductivity models with a conductance of 10^8 S of the lowermost mantle inferred from studies of nutation and precession of the Earth and decadal variations of length of day (LOD). The secular parts of equatorial rotations are less sensitive to these parameters, but the magnitude for the axial rotations is much smaller than for frictionless model. These models, however, produce oscillating parts in the equatorial rotations of both cores and also in the axial rotations of the whole Earth and outer and inner cores. These oscillations are sensitive to both the magnitude of radial magnetic field at the CMB and the conductivity structure. No sharp isolated spectral peaks are predicted for models with a thin conductive layer (~200 m) at the bottom of the mantle. In models with a conductive layer of ~100 km thickness, however, sharp spectral peaks are predicted at periods of ~225 and ~25 years for equatorial and axial rotations, respectively, although these depend on the strength of radial magnetic field at the CMB. While the present study is preliminary in modelling the fluid outer core and coupling mechanism at the CMB, the predicted axial rotations of the whole Earth may be important in explaining the observed LOD through interaction between the equatorial and axial rotations.

Keywords: Earth's rotation; Electromagnetic coupling; Core-mantle coupling; Earth's length of day; Glacial rebound; Mantle viscosity

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1. Introduction

Recent numerical works on the geodynamo have provided important clues on the flow, magnetic field and dynamics of the Earth's core tightly related to the rotational dynamics of the Earth (e.g. Glatzmaier and Roberts, 1995a,b; Kuang

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doi:10.1016/j.pepi.2005.08.004

and Bloxham, 1997, 1998), although these parameter regimes adopted in these simulations are far from those of the Earth. Glatzmaier and Roberts (1995a,b) indicated that the inner core rotates faster than the mantle (eastward drift). A first seismological evidence for the eastward rotation with $\sim 1^\circ\ \mathrm{year}^{-1}$ has been reported by Song and Richards (1996). More recently, however, Creager (2000) indicated that the inner core appears to be rotating slightly faster than the mantle at a rate of $\sim 0.2^\circ\ \mathrm{year}^{-1}$, and also the rotation rates obtained by Souriau and Poupinet (2003) are $0 \pm 0.2^\circ\ \mathrm{year}^{-1}$. The results by Kuang and Bloxham (1997, 1998) seem to explain several important factors associated with the geodynamo such as the field strength and spectrum at the core-mantle boundary (CMB) and the secular westward drift of the surface geomagnetic field (e.g. Bloxham and Jackson, 1991). Also, it seems possible to explain observed variations in the Earth's length of day (LOD) on a decadal timescale (Morrison, 1979; McCarty and Babcock, 1986; Herring et al., 1991) by adopting an electromagnetic (EM) coupling between the core and mantle, in which the fluid flow at the top of the core has been evaluated from surface secular variations of the magnetic field (e.g. Holme, 1998). Thus it has been generally accepted that the core dynamics plays important roles on the rotational dynamics of the Earth.

On the other hand, the surface mass redistribution associated with the Quaternary glacial cycles and its related Earth's deformation also cause variations in the Earth's rotation (Munk and MacDonald, 1960; Lambeck, 1980). Thus, it is geophysically meaningful to evaluate the effects of the Quaternary glacial cycles on the rotations of the Earth's core. Variations of axial rotation of the whole Earth, outer core and inner core, which are associated with the degree two ($n = 2$) Earth's deformation due to ice and water loads, are sensitive to the lower mantle viscosity and the magnitude of frictions at the CMB and inner core boundary (ICB) (Nakada, 2003), whereas Lefftz and Legros (1992a,b) and Lefftz et al. (1994) previously investigated the sensitivities of these factors to the differential rotation of the outer core. These studies with simplified viscous and EM frictions (Loper, 1975; Rochester, 1976), therefore, suggest that the differential rotations of both cores relative to the mantle depend on the magnitude of torques at the CMB and ICB.

It has been generally accepted that variations of LOD with a few milliseconds on decadal timescales, probably reflecting motions in the outer core described by torsional oscillations (Braginsky, 1970; Jault et al., 1988), are caused by exchanges of angular momentum between the solid mantle and fluid core. Four coupling mechanisms have been examined quantitatively in exchanges of angular momentum. Viscous coupling is associated with viscous drag at the CMB, and has been considered to be ineffective on decadal timescales (Rochester, 1984). Topographic coupling arises from non-hydrostatic pressure around irregular topographies of the CMB, and is sensitive to the magnitude of the irregularities (Hide, 1969, 1995; Jault and Le Mouël, 1991). Gravitational coupling due to density heterogeneities of both the mantle and inner core was first examined by Jault and Le Mouël (1989), and has been recognized to play an important role on the differential rotation between the mantle and inner core (Buffett, 1996, 1997, 1998). In particular, Buffett (1998) investigated the effects of topographic, gravitational and electromagnetic coupling mechanisms on decadal LOD by adopting continuous fluid cylinders describing torsional oscillations. Then, he indicated that the most viable coupling mechanism is due to the gravitational torques. However, Zatman (2003) suggested that the gravitational coupling is not a dominant form of core-mantle coupling on decadal timescales by examining flow at the core surface in the tangent cylinder electromagnetically coupled to the inner core.

Electromagnetic coupling caused by an interaction between the differential rotations of both cores and magnetic field (e.g. Rochester, 1962; Stix and Roberts, 1984) has extensively been examined for studying variations of LOD (e.g. Holme, 1998). For example, Holme (1998) indicated that a conductance of the lowermost mantle with 10^8 S or greater is required to explain observed decadal LOD by EM coupling. The Earth's nutation study by Buffett (1992) also indicated such a conductance. In order to evaluate EM torque at the CMB, it is required to estimate the fluid flow at the top of the core from observed secular variations of magnetic field. The flow field estimated by Holme (1998) is similar to that previously determined by Bloxham and Jackson (1991) that takes similar features as the secular variations based on the geodynamo calculation by Kuang and Bloxham (1997). Thus, the EM coupling may be a possible mechanism on decadal variations of LOD (e.g. Holme, 1998) and nutation and precession of the Earth (Buffett, 1992; Buffett et al., 2002). In this study, we also assume EM coupling at the CMB and ICB to examine the effects of the Quaternary glacial cycles on the differential rotations.

In order to study differential rotations associated with the Quaternary glacial cycles, Nakada (2003) employed the EM torques formulated by Loper (1975) and Rochester (1976). Loper (1975) and Rochester (1976) have evaluated the frictional torque acting at the CMB by ignoring time-dependent perturbations of magnetic field at the boundaries and flow in the outer core. That is, the forcing terms in their formulations are essentially independent of time, resulting in time-independent frictional torques. On the other hand, Buffett et al. (2002) evaluated the frictional torque associated