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A timescale of true polar wander of a quasi-fluid Earth: An effect of a low-viscosity layer inside a mantle

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ABSTRACT

By means of a simple parameter sensitivity analysis, we demonstrate the effect of a low-viscosity layer inserted inside a mantle of a hypothetical Earth on the timescale of large-scale and long-term true polar wander. Here the timescale in our parameter study means the characteristic scale of viscoelastic readjustment of the rotational bulge in the framework of the quasi-fluid approximation for the long-term reorientation of the Earth. Based on this assumption, we calculate the characteristic timescale and associated viscoelastic tidal Love number with the effect of this layer in order to see the dependences on the viscosity, depth, and thickness of the inserted layer. We also compute the characteristic timescale without this layer for the sake of comparison. Our results indicate that the timescale strongly depends on the existence of this layer: positive dependences on its viscosity and depth and a negative dependence on its thickness. We conclude that the low-viscosity layer has a strong impact on the characteristic timescale, especially if this layer exists at the top of the mantle. Although a few previous studies on the small-scale and short-term true polar wander have also suggested a possible effect of inserting a low-viscosity layer, our study implies that the sensitivity to the low-viscosity layer over a long timespan is not necessarily the same as that over a short timespan.

1. Introduction

1.1. Background

Large-scale and long-term true polar wander (TPW) on the terrestrial planets, particularly the Earth and Mars, has been theoretically and numerically investigated by several studies. Some of the studies on the large-scale TPW (Spada et al., 1992a; Spada et al., 1993; Spada et al., 1996; Ricard et al., 1993; Richards et al., 1997; Richards et al., 1999; Greff-Lefftz, 2004; Greff-Lefftz, 2011; Tsai and Stevenson, 2007; Rouby et al., 2008) are based on the quasi-fluid approximation whereas the others (Nakada, 2007; Nakada, 2008) are based on the iteration scheme, in order to solve the polar motion equation, or the so-called Liouville equation (Munk and MacDonald, 1960; Lambeck, 1980), in the form of the non-linear equation. A few recent studies based on the former approach (Harada, 2012; Creveling et al., 2012; Chan et al., 2014) even consider the stabilizing effect of non-hydrostatic figures memorized in elastic lithospheres (e.g., Willemann, 1984; Matsuyama et al., 2006).

These theoretical and numerical studies on the large-scale TPW are considered essential for a quantitative understanding of actual long-term rotational evolution. For example, mainly based on paleomagnetic circumstantial evidence, possible TPW events on the Earth (e.g., Van der Voo, 1994; Maloof et al., 2006; Steinberger and Torsvik, 2008; Mitchell et al., 2010a; Mitchell et al., 2010b; Torsvik et al., 2012) and Mars (e.g., Sprenke and Baker, 2000; Hood et al., 2005; Boutin and Arkani-Hamed, 2006; Langlais and Quesnel, 2008) have been inferred. Such large-scale TPW scenarios needs to be interpreted theoretically as well. The above-mentioned TPW modeling enables us to physically examine their validity (e.g., Creveling et al., 2012).

The reconstruction of the physical conditions which explain the hypothetical TPW events is expected to further put some additional constraints on past thermal states of the planets. This is because the TPW speed generally depends on the internal structure, especially the viscosity structure. In particular, in the case of the long-term TPW, one of the factors governing its speed is T_1 (see the next section), that is, the characteristic timescales of readjustment of the rotational bulge. This factor is determined by the viscoelastic relaxation modes of the tidal Love number (e.g., Peltier, 1974; Wu and Peltier, 1982), and hence, by the viscosity structure.

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In the conventional modeling of the large-scale TPW, heterogeneity on the viscosity structure of the mantle in terms of a potential impact of a low-viscosity layer (LVL), has not necessarily been dealt with. In fact, a large variety of geophysical observations tells us that the Earth's interior may include one layer or more with a large viscosity difference between its inside and outside, inserted at the upper (e.g., Klein et al., 1997; Forte and Mitrovica, 2001; Pollitz, 2003; Hearn, 2003; Dixon et al., 2004; Mitrovica and Forte, 2004; Steffen and Kaufmann, 2005; Kawakatsu et al., 2009) and/or lower (e.g., Nakada and Karato, 2012; Nakada et al., 2012) part(s) of the mantle. In addition to the Earth's mantle, there is a similar possibility that the Mars' mantle also possesses this kind of remarkable viscosity contrast based on tidal dissipation (Bills et al., 2005) and also the numerical simulation of the mantle convection with the influence of water inclusion (Ogawa and Yanagisawa, 2012). Nevertheless, in the previous studies, the viscosity structure has been roughly averaged, and therefore, assumed to include no mechanically-specific layer as above.

A few exceptional studies investigated the potential impact of the LVL on relatively small-scale and short-term TPW induced by the glacial isostatic adjustment (GIA). The exceptions are Milne et al. (1998) and Nakada and Okuno (2013), each of which explored the effect of the LVL inserted at the base of the upper or lower part of the mantle, respectively, on the secular rotational variation of the Earth. The impact of a shallower LVL on the TPW speed is small while that on the secular variation of the rotation rate (i.e., $\dot{J_2}$) is large. In contrast, the impact of a deeper LVL on the TPW speed is large while that on $\dot{J_2}$ is small. Although the spatial and temporal scales of the TPW in their studies are not the same as those addressed here, it is considered to be possible that the LVL at some depth also has a non-negligible influence on the speed of the large-scale TPW.

1.2. Purpose

In this paper, we show how the characteristic timescale of the large-scale TPW depends on the viscosity, depth, and thickness of the LVL inside the mantle, by giving the internal structure of a simplified Earth model, but with inclusion of an LVL effect. Here we suppose the long-term TPW which timescale allow us to apply the quasi-fluid approximation. Because the TPW speed strongly depends on the parameter T_1 for such a timescale as described above, we focus on the dependence of T_1 on the interior structure.

2. Parameters & methods

2.1. The characteristic timescale of readjustment of the rotational bulge (T_1)

Under a timescale long enough to allow the quasi-fluid approximation, the magnitude of T_1 represents the viscoelastic delay of the hydrostatic readjustment with respect to the excursion of the spin pole. The definition of T_1 has been described in several papers, such as Eq. (8) in Ricard et al. (1993), Eq. (3) in Spada et al. (1996), and Eq. (5) in Greff-Lefftz (2004). This value has a dimension of time and, in the case of the long-term TPW as mentioned in here, affects the timescale in which the rotation axis settles to the equilibrium position.

Regardless of the presence or absence of the stabilizing effect due to the non-hydrostatic form, T_1 is one of the important controlling factors to understand the characteristic timescale of the large-scale and long-term TPW. For example, in both cases, the non-linear Liouville equation is simplified as Eq. (82) in Harada (2012) for an axially symmetric load. This equation makes it clear that, for a certain load evolution, a larger T_1 results in a slower TPW. This tendency is even more obvious in the analytic solution for a linearly increasing load, for example, shown in Eq. (7) in Spada et al. (1996) and Eq. (100) in Harada (2012) for the case without the non-hydrostatic effect. In such a simple load formation, the TPW timescale is mostly proportional to T_1 if the timescale of the load formation is relatively short (if not, the viscoelastic delay related to T_1 is no longer dominant, and thus the TPW timescale is controlled by the loading timescale). This point is nearly the same even considering the non-hydrostatic effect due to the elastic lithosphere as in Eq. (103) in Harada (2012).

The objective of the present calculation is mainly to clarify the sensitivity of this T_1 value to the LVL effect. As in the definition cited above, T_1 is not simply expressed as the sum of the relaxation timescales (i.e., $-1/s_i$) of the viscoelastic modes. Rather, in T_1, each of the relaxation timescales is associated with its relaxation strength (i.e., $-k_i/s_i$) for tidal deformation assigned as a weighting factor. As a consequence, T_1 is not generally equal to the viscoelastic timescale of the tidal deformation itself although a uniform Newtonian (not Maxwellian) planetary body is an exceptional case (e.g., Tsai and Stevenson, 2007) as derived in Appendix A.3 of Harada (2012). All of the timescales and strengths for the relaxation modes reflect the internal structure, that is, the density, elasticity, and viscosity profiles. This structure dependence of T_1, especially on the viscosity structure, is investigated by defining the parameter sets as described below.

It should be mentioned here that any driving force for TPW is out of scope in the present study. In fact, as shown in Eq. (16) in Ricard et al. (1993) and Eq. (1) in Spada et al. (1996), the timescale is directly proportional to the difference between the maximum and minimum moment of inertia $C - A$ as well as T_1, and also inversely proportional to excitation E. That is, the real time constant of TPW is $T_1(C - A)/E$ rather than T_1. In general, depending on how large this normalized excitation $E/(C - A)$ is, the actual TPW timescale is a few orders of magnitude longer than T_1. However, as mentioned already, the aim of this study is to focus just on T_1 under the LVL effect. Therefore, $E/(C - A)$ is not discussed in here.

2.2. Invariable parameters: Density and elasticity profiles

The baseline density and elasticity structure model of the Earth for the present calculation is given in Table 1. This is exactly the same as that used in Bills and James (1997), following those originally used in Yuen et al. (1983) and Sabadini et al. (1984). See Table 1 of Bills and James (1997), although the viscosity structure in their table corresponds to the model Y2121 in their notation, not Y2122 as shown in Table 1 in here. For numerical convenience, as in this table, a largely simplified model compared to more realistic models (cf., Gilbert and Dziewonski, 1975; Dziewonski and Anderson, 1981) is assumed in the computation. Also, assumed for each solid layers are incompressible media, and therefore only rigidity is given as an elastic modulus. However, this simplification does not necessarily affect the validity of the subsequent discussion since the main aim at the current time is just to see the potential impact of the LVL.

2.3. Variable parameters: Viscosity profiles

The baseline viscosity structure model of the Earth for the present calculation is also given in Table 1. This is exactly the same as that defined in Nakada and Karato (2012). See R0 shown in Fig. 1 of Nakada and Karato (2012). Once again, for the sake of the calculation based on the assumption of incompressibility, the viscosity profile is simplified as well as the density and elasticity profiles, except for the presence of the LVL as mentioned below. In this