Earth and Planetary Science Letters 502 (2018) 126–132

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

What drives 20th century polar motion?

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ARTICLE INFO

Article history:
Received 3 July 2018
Received in revised form 23 August 2018
Accepted 31 August 2018
Available online xxxx
Editor: J. Brodholt

Keywords:
Earth rotation
polar motion
glacial isostatic adjustment
surface mass transport
mantle convection

ABSTRACT

Astrometric and geodetic measurements show that the mean position of Earth's spin axis drifted through the solid crust toward Labrador, Canada at an average speed of 10.5 ± 0.9 cm/yr during the 20th century. Understanding the origins of this secular polar motion (SPM) has significance for modeling the global climate, as it provides a link to ice mass balance and sea-level rise. A perplexing issue, however, is that while glacial isostatic adjustment (GIA) models satisfactorily explain the direction of SPM, the associated prediction of the amplitude is insufficient. Our Bayesian GIA analysis, with constraints from relative sea-level and vertical land motion data, reveals that this process only accounts for $33 \pm 18\%$ of the observed SPM amplitude. This shortfall motivates a more broadly scoped reassessment of SPM drivers. To address this, we assemble a complete reconstruction of Earth's surface mass transport derived from recent advancements in modeling the global 20th century cryospheric, hydrologic, oceanic, and seismogenic mass exchange. The summed signals, nonetheless, cannot fully reconcile the observed SPM, even when considering the error statistics of each driver. We investigate an additional excitation source: changes in Earth's inertia tensor caused by mantle convection. Sophisticated models have recently been advanced in tectonic plate reconstructions, in conjunction with geoid and seismic tomographic models. Here we use these models to compute new estimates of SPM. While the convection-driven SPM has considerable uncertainty, the average direction of 283 recent models aligns with the residual SPM (within $2.7° \pm 14.8°$), significantly reducing the gap between observation and prediction. We assert that one key mechanism for driving 20th century SPM is long-term mass movement due to mantle convection.

1. Introduction

The study of the movement of Earth's spin axis through the Earth's crust in the astrometric and space geodetic observing era (1899–present) may be divided into at least four elements that differ by their respective timescales: hours to weeks generally involve tides, winds and atmospheric/oceanic forcings; annual and 433-day Chandler periods involve global solar related forcing and a free wobble, respectively; interannual, interdecadal and 30-yr Markowitz periods involve global hydrological and cryospheric forcings, possibly modified by a subtle core-mantle coupling. The subject of this paper involves the remaining timescale of observation: a secular movement of the spin axis since 1899. Combining all available estimates (Gross, 2007) suggests that the spin axis drifted along $74.2° \pm 4.7°$ west longitude at a speed of 10.5 ± 0.9 cm/yr during the 20th century (Fig. 1a). The basic theoretical relationship of Earth's surface and interior mass transport and changes to the inertia tensor, and hence polar motion, is well known (Sabadini and Peltier, 1981; Wu and Peltier, 1984; Spada et al., 1992; Ricard et al., 1993a; Vermeersen et al., 1997; Mitrovica et al., 2005). The question, however, is the following: which aspects of mass transport are dominant drivers of the 20th century SPM?

Here we analyze two of the Earth's interior viscous mass transport processes that have much longer timescales than the polar motion observations themselves: GIA and mantle convection that operate on timescales of thousands to tens of millions of years. In addition, we comprehensively account for contemporary environmental forcings that involve global surface mass transport (e.g., glaciers and ice sheets imbalances, sea-level change) and the net

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https://doi.org/10.1016/j.epsl.2018.08.059

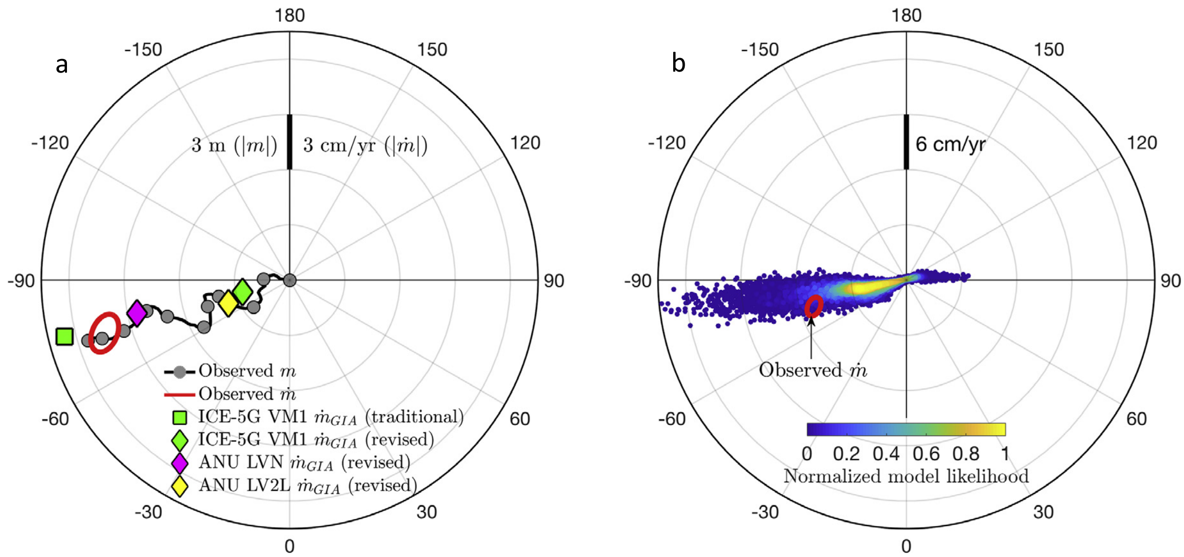

Fig. 1. GIA and the 20th century SPM. **(a)** Observed and modeled rates of SPM, $\dot{m}$. All model predictions, $\dot{m}_{GIA}$, are solely due to GIA processes. The predictions differ in assumed deglaciation history (ICE-5G, Peltier, 2004; or ANU, Lambeck et al., 2010, 2014) and in mantle viscosity profile (VM1, Peltier, 2004; LVN or LV2L, Nakada et al., 2015). The restoring torque effect is highlighted by showing predictions (green markers) computed by using the "traditional" (Wu and Peltier, 1984) or the "revised" ice age rotational stability theory (Mitrovica et al., 2005). Even after accounting for the improved rotational stability, some models nonetheless predict significant $\dot{m}_{GIA}$ (magenta diamond; see also Mitrovica et al., 2015). Inclusion of a low viscosity D'' layer, however, dampens the amplitude (yellow diamond). This non-uniqueness in $\dot{m}_{GIA}$ solutions motivates the statistically robust new Bayesian assessment (see panel b). Observed mean pole positions, $m(t)$, relative to 1900 is shown (data courtesy of International Earth Rotation and Reference Systems Service: https://www.iers.org/) to note that the spin axis does not drift in a precisely linear path. A low pass filter having a 6-yr window allows interannual signals to be seen. Gray circles represent the mean annual positions at 10-yr time intervals. The same scale bar with differing metric is used for m and $\dot{m}$. **(b)** Our predicted $\dot{m}_{GIA}$ for 128,000 models. The color scale represents the likelihood of a given model – normalized by the best-fit model probability – to explain the global RSL/GPS data. Our predictions generally align with the observed $\dot{m}$, with many (less-likely) models fully reconciling the observation. The Bayesian statistics suggest that GIA accounts for only $33 \pm 18\%$ of the observed SPM amplitude. Note that we have different scales on panels a and b.

effects of seismic deformation, in order to deliver a new, multidisciplinary, and unified explanation to the 20th century polar motion.

2. Glacial isostatic adjustment

It has been argued throughout the last four decades that slow viscous mantle flow in response to many cycles of Late Pleistocene glaciation drives the observed SPM (Sabadini and Peltier, 1981; Wu and Peltier, 1984; Vermeersen et al., 1997). For a reasonable choice of deglaciation history, solid Earth structure, and material parameters (especially lower mantle viscosity), it is indeed possible to construct a GIA model that matches both the direction and amplitude of observed SPM almost entirely (Fig. 1a). This simple explanation, however, is highly problematic because it ignores the changes in Earth's inertia tensor accompanying an unequivocal rise in global mean sea-level (GMSL) during the 20th century (Munk, 2002; Mitrovica et al., 2015). One recent breakthrough in our understanding of GIA processes, for example, is the recognition of an important restoring torque due to the background long-term triaxiality of the Earth's inertia tensor (Mitrovica et al., 2005). Such necessary improvements in the GIA model generally dampen the predicted SPM amplitudes (Fig. 1a). Consequently, it has become rather widely accepted that non-GIA processes should be integral to explaining the observed SPM (Cambiotti et al., 2010; Mitrovica and Wahr, 2011; Nakada et al., 2015). Quantifying the relative importance of such contributions, however, has been hampered by the relatively poorly treated statistics of the GIA predictions of SPM.

Here we employ a GIA model (Caron et al., 2018) that operates on a robust Bayesian statistical framework (Supplementary Methods Section 1). Our model has a radially symmetric solid Earth structure, with one lithosphere and two mantle layers, that may be sufficient to evaluate statistics of low-degree gravity coefficient change and resulting polar motion. We assemble a global distribution of paleo relative sea-level (RSL) data from 11,451 sites and Global Positioning System (GPS) data from 459 stations. We have carefully selected these data sets and corrected, when applicable, for contemporary ice loss to ensure that these are minimally contaminated by non-GIA signals. We build a cost function, to be minimized, by ingesting all of these global data sets into our Bayesian framework, with a proper accounting of data uncertainty and redundancy, in order to explore the parameter space related to solid Earth structure and deglaciation history simultaneously. One approach often taken is to use the observed polar motion as a necessary constraint on lower mantle viscosity structure (Kaufmann and Lambeck, 2002). Here we do not provide such rotational constraints because our goal is to cleanly quantify GIA-driven SPM, given that other drivers are present. Our Bayesian analysis therefore unburdens the GIA model from seeking full reconciliation of observed SPM. What emerges is the probability distribution function – based on a set of 128,000 model realizations – for the present rate of GIA-driven SPM (Fig. 1b).

It is important to appreciate the sensitivity of the predicted SPM with respect to the GIA model parameters. Here we explore a total of eight parameters (Fig. 2), three of which are related to solid Earth structure and five to the relative ice volumes involved in deglaciation since the Last Glacial Maximum. The glaciation parameters basically scale the ice volume of the reference ice models (Lambeck et al., 2010, 2014) in five different regions independently. Fig. 2 suggests the following two key points: (1) as noted in past studies (Sabadini and Peltier, 1981; Vermeersen et al., 1997; Mitrovica and Wahr, 2011; Nakada et al., 2015), SPM predictions are most sensitive to lower mantle viscosity; and (2) as depicted by the clustering of "likely" models, all of the model parameters are fairly well resolved by the constraining data sets. Our preferred models have upper and lower mantle viscosities in the respective ranges of $(3.6–10) \times 10^{20}$ Pa s and $(7–73) \times 10^{21}$ Pa s. These are in agreement with the average profiles of many GIA models (Cambiotti et al., 2010; Lambeck et al., 2010, 2014), including those that