Excitation of the Earth's Rotational Axis by Recent Glacial Discharges

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Abstract. We study the effects of present-day glacial discharges and the growth of the Antarctic ice sheet on exciting the Earth's rotational axis. Glacial forcing could cause a maximum change in J2 of about one-third of the observed amount, for the Maxwell rheology and for Burgers' body models with a long-term, lower-mantle viscosity greater than about 1023 Pa s. For transient rheologies the amount of excitation due to glacial melting decreases. Polar wander is not much excited by recent glacial melting for the various types of rheologies examined.

Introduction

In the past few years there has been a great flurry of activity in estimating mantle viscosity structure from rotational data obtained from satellite and astronomical observations (e.g. Sabadini and Peltier, 1981, Yuen et al., 1982, Yuen and Sabadini, 1985, Yoder et al., 1983, Peltier, 1983 and Wu and Peltier, 1984). In all of these investigations the source of the forcing has been attributed solely to melting from the last deglaciation. Recently Yoder and Ivins (1985) have raised the point that these present-day variations in the Earth's rotation may be induced in part by the ongoing retreat of temperate latitude glaciers (Meier, 1984). Since inference of the deep mantle viscosity, applicable for theory of mantle convection, is very dependent upon the actual value of the LAGEOS acceleration data due solely to Pleistocene deglaciation (Yuen and Sabadini, 1985), it is of extreme importance to evaluate the potential contaminating effects on secular rotation from ongoing glacial melting.

In this report we wish to assess the role played by ongoing glacial forcing (Meier, 1984) and by the possible recent growth of the Antarctic ice sheet (D.O.E. report, 1985) in producing secular rotational motions. As the timescales involved are of the order of hundreds of years, the need for considering transient rheology in this case becomes more crucial than in the case of Pleistocene deglaciation (Sabadini et al., 1985). We shall demonstrate, in fact, that for the time window of interest there are substantial differences in the behavior of the rotational responses for transient and steady-state rheologies.

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Paper number 6L6110.
0094-8276/86/006L-6110$03.00

Physical mechanism

It may seem curious that discharges from valley glaciers, such as those found in Alaska and in the Himalayas, whose typical mass is about 1024 of the former Laurentide ice sheet, could conceivably be competitive with Pleistocene ice sheet, due to glacial retreats is fundamentally different from the Pleistocene forcing in two respects. One must recognize that glacial forcing is an ongoing process, as opposed to the last deglaciation of the ice age which terminated some 7,000 years ago. Hence, we, as observers today, are much closer to the current glacial retreating events. In contrast, the rate of melting associated with glacial discharges is only 5% of the characteristic rate of global sea-level rise occurred in the last glacial maximum, which was about 10 mm/yr.

In order to evaluate forced responses in a viscoelastic medium, one must consider not only the magnitude of the forcing, which to some people appears to be the overriding factor, but also, equally important, the time elapsed and the rate of the forcing. All of these factors appear explicitly in any time-dependent solution of geodynamical processes. Lastly, for timescales less than a few hundred years one must take into account the possibilities of transient rheology. We are led, therefore, by the above considerations to carry out explicit calculations for assessing the potential contributions made by current glacial melting to rotational motions.

Calculational procedures

Calculations are carried out following the analytical formulation given in Yuen et al. (1982), Sabadini et al. (1984) and Yuen and Sabadini (1985). The thirty-one glaciers tabulated in Meier (1984) are employed as point-source forcings, in which the geographical locations are supplied as part of the input function. For the purpose of studying long wavelength responses, such as those involved in rotation, Sabadini et al. (1982) have shown that the simplified model of a global ocean surrounding an ice disc is perfectly adequate and that very little changes are brought about by the use of more realistic ocean functions (Munk and MacDonald, 1960). To model the glacial forcing we have assumed that each of the glaciers has grown to a maximum mass M_i by the year 1400 A.D. where M_i is estimated by the product of the...
present-day melting rate (Meier, 1984) of the individual glacier and a period of 200 years between 1200 and 1400 A.D. which is used here as a characteristic timescale representing glacial dynamics.

As there are not many data constraining the melting history of glaciers, we will employ a simple time history in order to bring out the physics of ongoing excitation. We assume that the glaciers have existed in steady-state since 1400 A.D. and that glacial melting has been occurring since 1900 A.D. It should be noted that this chronology is only approximate. The time function is represented by two parameters: b the timespan of a steady-state glacier (b = 500 yr in this work) and a the timescale over which significant glacial melting takes place (a = 200 yrs). We have employed in the forcing a scaling factor between the average mass balance over this century and the average annual amplitude of each glacier (Meier, 1984).

The time-dependent viscoelastic responses for the polar speed \( m(t) \) and the secular variation of the gravitational coefficient \( J_2(t) \) from the ongoing excitation are given by (e.g. Sabadini et al., 1984)

\[
m(t) = \frac{-3G}{4\pi^2} \left[ \sum_{i=1}^{L} \cos \theta_i \sin \phi_i M_i e^{i \phi_i} \right] \\
x \left[ \lambda_i R_0 (H(t) - \frac{(t-b)}{a} H(t-b)) + \sum_{i=1}^{M} A_i \left( (1 + \lambda_0 + \sum_{j=1}^{M} \frac{1}{\alpha_j - \alpha_i}) \right) [H(t)e^{i \phi_i} + \frac{1}{a_{\phi_i}} (1 - e^{i \phi_i (t-b)} H(t-b))] \right] (1)
\]

\[
\frac{dJ_2}{dt} = \sum_{i=1}^{L} \left( 1 - 3 \cos^2 \theta_i \right) M_i \left[ \frac{1 + \lambda_0}{a} H(t) - \sum_{j=1}^{M} I_{ij} e^{i \phi_i H(t)} \right] + \sum_{j=1}^{M} \frac{1}{a_{\phi_i}} \left( e^{i \phi_i (t-b)} - 1 \right) H(t-b) \right] (2)
\]

The gravitational constant is given by \( G \), the earth’s radius and mass by \( d \) and \( M_0 \), respectively, the diurnal rotation rate by \( \Omega \), the latitude and longitude of each glacier by \( \theta_i \) and \( \phi_i \), the total number of glaciers by \( L \). The inverse relaxation times of the normal modes associated with isostatic and rotational relaxation are denoted respectively by \( \beta_i \) and \( \alpha_i \) (Sabadini et al., 1984) respectively. The total number of modes is given by \( M \) and depends on the rheology and stratification of the model. The isostatic factor and the elastic contribution to the moment of inertia are represented respectively by \( R_0 \) and \( I_0 \). A detailed description can be found in Sabadini et al. (1984) and Yuen et al. (1982). It should be noted that the non-exponential terms in both (1) and (2) arise as a consequence of the continual forcing. They are not present in the case of responses to Pleistocene deglaciation, an already finished event.

Rotational excitation by glacial discharges

Since the time span of interest is shorter than a few hundred years, it is essential to consider the effects of transient rheology. Yoder and Ivins (1985) only took the steady-state Maxwell rheology into their analysis. The rheology which best exemplifies transient and steady-state behavior in the mantle is the Burgers’ body rheology (Yuen and Peltier, 1982; Sabadini et al., 1985). We will compare both Maxwell and Burgers’ body models and consider two different types of viscosity stratification. The first is a three-layer model consisting of an elastic lithosphere, a viscoelastic mantle, which may have either steady-state or transient rheology, and an inviscid core. In the second class of models the upper mantle above 670 km depth is assumed to have a steady-state Maxwell viscosity of \( 10^{22} \), while in the lower mantle the possibilities of both transient and steady-state creep will be explored. Due to the short timescales involved, it is of importance to allow for the possibility that the entire mantle may behave in a transient rheological manner.

In Fig. 1 we display the results for \( J_2 \) excitation from glacial forcing for the 3-layer (panels a and b) and 4-layer (panels c through f) models. In the 4-layer models, the interface in the mantle for these short timescales, less than 500 yrs, is allowed to deform in nonequilibrium response to the restoring force from the density jump at 670 km depth (Christensen, 1985).

The ratio of the elastic moduli \( \mu_2/\mu_1 \) and of the short to long-term viscosities \( \nu_2/\nu_1 \) in the Burgers’ body rheology have been varied considerably. It can be observed that low values of \( \nu_2/\nu_1 \) and \( \mu_2/\mu_1 \) help to decrease rapidly the transient responses, whereas the signals remain relatively unattenuated.
The effects from a rise of the global sea-level are to induce a decrease in the spin-rate with an increase in $J_2$ which is opposite in sign to the observation of $-3 \times 10^{-11}$ yr$^{-1}$ (Yoder et al., 1983) obtained from analysis of Lageos' orbital residuals. If the long-term viscosity of the mantle is $0(10^{23})$, the $J_2$ signatures produced by transient rheology constitute about 20% of the observed value for $t$ greater than 50 yrs, and for $\nu_S/\mu_S$ and $\nu_L/\mu_L$ both less than 0.1. Otherwise, the contributions from glacial discharges can be a significant fraction of the observation, especially for a stiff lower mantle with steady-state viscosities exceeding $10^{23}$P (cf. panels (e) and (f)). There are clearly discernible differences between transient and steady-state rheologies but, more interestingly, also between Burgers' body models with vastly different long-term viscosities in the lower mantle.

As the Antarctic ice sheet lies near the rotational axis, any significant mass exchange between land and ocean would have more of an impact upon $J_2$ than upon polar motion. There are evidences (D.O.E. report, 1985) suggesting that the Antarctic ice sheet most likely is getting larger, therefore taking water out of the sea. We have carried out calculations of $J_2$ excitation due to growth of the Antarctic ice sheet, in which the mass accumulation is modelled as a point-source, located at the south pole. We have assumed that this growth phase began in 1900 A.D. and proceeded with two possible rates, (D.O.E. report, 1985) namely, $-6$ mm/yr and $-2$ mm/yr in the global sea-level. Prior to 1900, it is assumed that there is no mass flux between Antarctica and the surrounding oceans. The growth of the Antarctic ice sheet excites $J_2$ with the same sign as for Pleistocene melting, since the axial moment of inertia decreases as a consequence. The results are displayed in Fig. 2 for both the 3-layer (panel a) and 4-layer (panel b) models. Two different steady-state, lower mantle viscosities $\nu_{LM}$ are included for comparison in the case of forcing with $-6$ mm/yr (panel b). From inspection of the figure, it is clear that the upper-bound estimate for the growth-rate of Antarctica would produce $J_2$ variation close to the observed value, if the mantle were to have steady-state rheology throughout (panel a, b) or a sufficiently high steady-state viscosity in the lower mantle (panel b). Smaller rates of growth would not seriously impair the interpretation that the observed $J_2$ is caused for the most part by Pleistocene forcing.

Polar wander excited by glacial discharges is calculated according to eqn. (1). The geographical locations of the two largest glaciers, Alaska and Himalayas, are such as to nearly cancel each other in the polar excitation, in contrast to the case of $J_2$ variation, in which the contributions to the axial moment of inertia reinforce one another. This phenomenon is illustrated in Fig. 3 where the polar speeds are plotted for both the 3- and 4-layer models. The velocities attained for transient rheologies are higher than those derived from the Maxwell models (dashed curves). The initial direction $\phi_i$ for the glacial forcing is $177^\circ$E which is nearly opposite to the observed secular direction of $76^\circ$W (Dickman, 1977). After a short period the polar wander heads in a direction $3^\circ$W but with a magnitude which is at most a few percent of the observed polar velocity of $0.003$ arc sec/yr (Dickman, 1977). These results clearly demonstrate that recent glacial forcings contribute much more to $J_2$ than to polar wander.

To conclude, we find that present-day glacial discharges can potentially contribute in a significant way to the observed $J_2$ value. The maximum effect would be to change $J_2$ due to the last deglaciation by $33\%$ to $-4 \times 10^{-11}$ yr$^{-1}$. Effects from Antarctica's growth can be quite significant and can conceivably account for the entire $J_2$ signal.

References


D.O.E. Report, Glaciers, ice sheets, and sea level: effect of a...


