ATTACHMENT 2

CLIMATIC IMPLICATIONS OF ISOSTATIC ADJUSTMENT CONSTRAINTS ON CURRENT VARIATIONS OF EUSTATIC SEA LEVEL

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ABSTRACT

Two different types of geophysical data have recently been invoked to support the notion that the mass of water in the global ocean is increasing. These consist of local tide-gauge measurements of relative sea level and measurements of the wander of the Earth's pole of rotation with respect to the surface geography. This paper reviews recent analyses that demonstrate that the former data are significantly contaminated by ongoing changes of sea level forced by the melting of Würm-Wisconsin ice that occurred in the time interval 6-18 KBP. The latter observations, on the other hand, are entirely explicable as a response due to the same causative agency. These analyses therefore suggest that the rise in mean global sea level that appears to be required by the tide-gauge data may be steric in origin.

INTRODUCTION

In the recent geophysical literature considerable attention has been addressed to the question of whether a significant change in global climate has occurred during the past 100 years, that is, since the beginning of the industrial revolution. Indeed such change is expected owing to the increase in atmospheric CO_2 (and aerosol) load caused by the burning of fossil fuels, an increase that is now well documented. Because of the large intrinsic variability of annually averaged atmospheric temperature, it is not expected that this anthropogenically induced climatic amelioration would be directly detectable as yet, however, and there has been considerable interest in proxy records that might provide a clearer, if less direct, indication of the expected effect. One such class of proxy records that could potentially provide the desired information consists of data sensitive to variations of the mass of water in the global ocean. The idea that has motivated interest in such data is simply that a slight amelioration in global climate might be associated with a more significant warming in the polar regions and thus cause a detectable decrease in the mass bound in polar, or somewhat lower-latitude alpine, ice complexes. If the volume of continental ice <u>is</u> decreasing then there should be evidence of this in several different oceanographic and geophysical data sets. The most obvious such data are those recorded on tide gauges, many of which have been installed for sufficient lengths of time (50 or more years) that any significant trend of relative sea level should be easily extracted. One less obvious type of data, which might be equally useful in establishing the existence of such an effect, consists of astronomical observations of fluctuations in the Earth's rotation. Because of the variations in the elements of the planetary inertia tensor that are forced by redistribution of the surface mass load during ice-sheet melting, both the length of day and the location of the rotation pole with respect to the surface geography should exhibit astronomically detectable changes. The latter data have the additional useful characteristic that they are only sensitive to the shift in surface mass load. On the other hand any sea-level trend observed in tide-gauge data is ambiguous in the sense that it might equally well be explained by invoking a change in water volume caused by thermal expansion or contraction as by a change in water mass.

In fact both of these types of data have recently been invoked in support of the notion that there is an increase of the mass of water in the global ocean currently taking place. Both Gornitz et al. (1982) and Barnett (1983) have interpreted a global array of tide-gauge-based relative-sea-level (rsl) measurements as revealing an ongoing increase of water volume. Best estimates of the expected steric (thermal expansion) contribution to this increase have been interpreted to suggest that this effect cannot entirely account for the observation. Meier (1984) argued on the basis of direct glaciological evidence that the small (alpine) glaciers of the world are the most likely source of at least part of the required meltwater. A significant problem with interpretation of rsl data from the global tide-gauge network is that the observations are significantly contaminated by isostatic adjustment effects (e.g., Peltier 1982). Although the melting of Würm-Wisconsin ice was complete by approximately 6000 years ago, relative sea level continues to change on this account because of the slow return to isostatic equilibrium, which is due to the high value of the viscosity of the Earth's mantle. In sites located in the regions immediately peripheral to the Laurentide and Fennoscandian ice sheets, relative sea level is rising at present owing to the decrease of local planetary radius caused by the viscous flow of material back into the regions that were once ice covered. This effect may be important since a large number of tide gauges are located in such regions (U.S. east coast, European west coast). One of the purposes of this paper is to discuss a method that has been developed that is suitable to filter isostatic adjustment effects from the tide-gauge data and thereby to reveal more clearly any residual effect that might exist. This analysis will be discussed in the next section of this paper.

The second class of data that has also been suggested as requiring some present-day disintegration of continental ice consists of the observed wander of the rotation pole toward eastern Canada at a rate near 0.95 degree per million years. The history of the position of the rotation pole has been recorded since the turn of the century by the International Latitude Service (ILS) (e.g., Vincente and Yumi 1969, 1978), and the polar wander revealed in it was interpreted by Munk and Revelle (1955) as requiring some current variation of the surface ice load. Recent analysis has demonstrated, however, that this interpretation of Munk and Revelle is incorrect. Arguments reviewed in the third section of this paper, establish rather conclusively that the observed wander of the rotation pole in the ILS path is entirely explicable as a memory of the planet of the last deglaciation event of the current ice age. Furthermore, the nontidal acceleration of the Earth's rotation, recently inferred on the basis of the orbit of the LAGEOS satellite, is also entirely explicable as a memory of the melting of Würm-Wisconsin ice (Peltier 1983). These data together appear to restrict severely the magnitude of any ongoing reduction of the volume of continental ice. The implications of isostatic adjustment contamination of both the tide-gauge data and Earth-rotation observations to the climate-change issue are discussed in the concluding section.

FILTERING THE TIDE-GAUGE DATA TO REMOVE ISOSTATIC ADJUSTMENT EFFECTS

Over the past decade, beginning with the paper by Peltier (1974), a complete gravitationally self-consistant model has been developed that is able to predict rather accurately the variation of relative sea level that should be observed anywhere on the Earth's structure due to ice sheet disintegration. A recent summary of this research will be found in Peltier (1982). To date the model has been exclusively employed to predict rsl changes due to the melting event that began 18,000 years ago and ended about 6000 years ago that saw the disappearance of large ice sheets from Canada and Fennoscandia and reduction of the ice in West Antarctica. By comparing the predictions of this model with the ^{14}C record of rsl change over the time since melting began, it has proven possible to infer the variation of effective planetary viscosity with depth. This parameter is a crucial ingredient in thermal convection models of the process of continental drift, and the inferred value of the mantle viscosity may be construed as verifying the validity of this convection hypothesis (Peltier 1985). Since the viscoelastic model does fit the ^{14}C record of deglaciation everywhere, it may be employed to predict the present-day rate of rsl variation anywhere where there is a tide gauge and thereby to filter from these "modern" oceanographic data the local effect due to present-day glacial isostatic disequilibrium. The way in which this analysis is done will be illustrated by considering sites from along the eastern seaboard of the continental United States shown on Figure 2.1.

The first step in the procedure is to establish accord between the predictions of the model and the ^{14}C record of rsl variations on the long time scale of these observations. A collection of such data published by Bloom (1967) from this region has recently been analyzed in Peltier (1984), who has argued that a good fit to them appears to require a lithospheric thickness somewhat in excess of 200 km if the mantle viscosity profile is fixed to a constant value of 10^{21} Pa s. The goodness of fit of this model to ^{14}C data from six sites along the U.S. east coast is illustrated by the comparisons in Table 2.1,

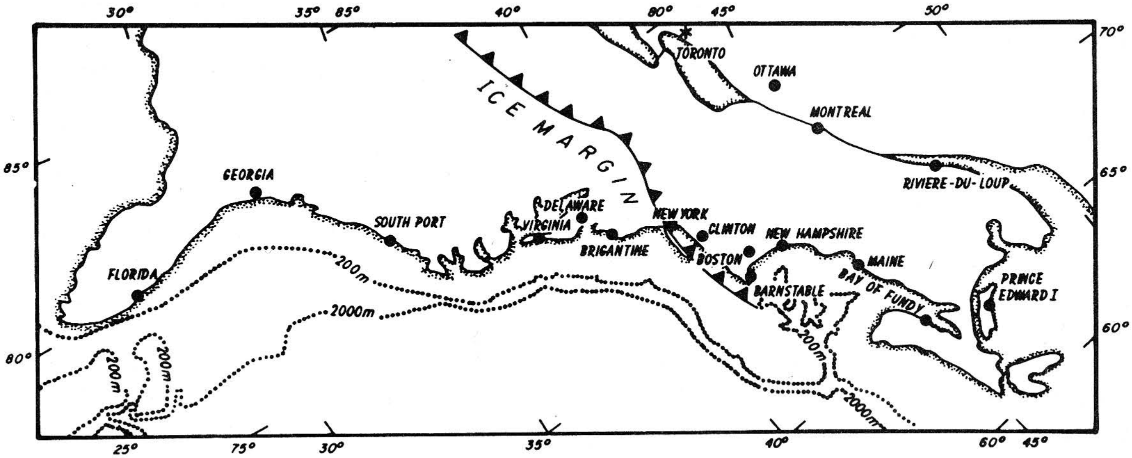

FIGURE 2.1 Sites along the U.S. east coast at which ^{14}C data exist that can be employed to fix the parameters of the viscoelastic model employed to filter the tide-gauge data.

which demonstrate that the model does explain the data rather well. We may therefore proceed to employ it to predict the rate of rsl rise that should be observed at any specific tide gauge along the coast and to subtract this prediction from any trend that may exist in the individual tide-gauge records. Barnett (1983) has shown that all tide gauges along this stretch of coast do in fact reveal a trend toward rising relative sea level as a function of time.

Figure 2.2(a) shows a preliminary plot of the residual (corrected) rsl trends at a larger number of east coast tide-gauge sites as a function of distance in radians from the site at Pensacola in Florida. Also shown in this figure as the horizontal line is the mean rate of rsl rise about which the residuals fluctuate. A more refined calculation suggests that the mean of the data corrected for isostatic adjustment effects is between 1.1 and 1.2 mm/yr. The average rate of submergence along the U.S. east coast due to this cause is near 0.8 mm/yr, so that the contamination is about 40 percent of the raw trends. For comparison purposes Figure 2.2(b) shows the corrected trends for tide-gauge sites along the U.S. west coast. Along this active continental margin there is no consistent signal revealed either before or after correction. This is hardly surprising given the intensity of tectonic activity in this region due to the presence of San Andreas transform fault. The east coast passive margin, however, provides a much more stable "float" for the inference of residual rsl variation, and the data from this region do seem to require that some process other than glacial isostatic adjustment is contributing to the observed submergence in this region at present. In attempting to understand what this effect is, it may be important to note that the tide-gauge data from almost all sites along this coast show that the local rates of sea-level rise decreased rather sharply after about 1940. This may be an important constraint on the candidate mechanisms that might be invoked to explain the observations. An additional constraint is that discussed in the next section.

TABLE 2.1 Observed and Predicted rsl (in meters) at Selected Eastern Seaboard Sites [a]

	Time, kyr								
Location	-8	-7	-6	-5	-4	-3	-2	-1	0
Southport									
Observed					-3.3 ± 0.5	-2.2 ± 0.4	-1.2 ± 0.2	-0.5 ± 0.1	0
Predicted					-2.26	-0.96	-0.30	-0.03	0
Virginia									
Observed	-22 ± 4	-17 ± 3	-13 ± 3	-10 ± 3	-7.0 ± 1.5	-3.0 ± 1.0	-0.5 ± 0.5	-0.4 ± 0.5	0
Predicted	-29.52	-21.70	-14.90	-9.63	-5.95	-3.45	-1.78	-0.68	0
New York									
Observed	-17.8 ± 3.0	-16.0 ± 2.4	-13.0 ± 2.2	-9.4 ± 1.5	-6.4 ± 0.6	-4.4 ± 0.5	-1.2 ± 0.3		0
Predicted	-22.48	-19.06	-14.45	-10.02	-6.56	-4.00	-0.88		0
Brigantine									
Observed				-10.5 ± 0.6	-7.5 ± 0.5	-5.2 ± 0.5	-3.0 ± 0.4	-1.4 ± 0.4	0
Predicted				-11.32	-7.79	-4.40	-2.36	-0.95	0
Clinton									
Observed		-10.2 ± 0.7	-8.4 ± 0.5	-6.7 ± 0.5	-4.7 ± 0.5	-3.4 ± 0.5	-1.0 ± 0.2		0
Predicted		-20.39	-15.5	-10.84	-7.16	-4.41	-0.94		0
Boston									
Observed				-9.0 ± 3.0	-6.0 ± 3.0	-2.5 ± 2.0	-0.5 ± 0.5		0
Predicted				-9.02	-6.03	-3.74	-0.84		0

[a] Calculations are based on the gravitationally self-consistent model with realistic ICE-2 melting chronology and an Earth model with a lithospheric thickness of 245 km and 1066B elastic structure.

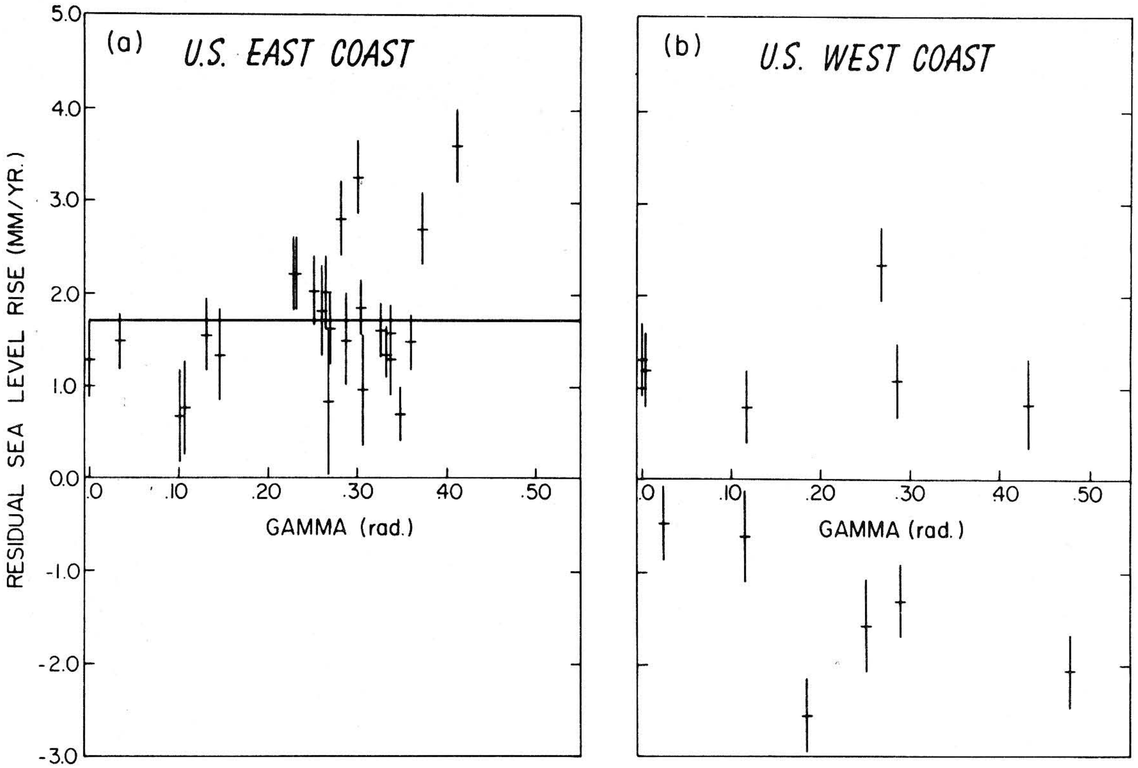

FIGURE 2.2 Relative sea-level trends from tide-gauge data along the U.S. east (a) and west (b) coasts in the period since 1940 corrected for isostatic adjustment effects.

EARTH ROTATION AND ICE-SHEET DISINTEGRATION

The ILS record of polar motion shown in Figure 2.3 is dominated by oscillatory variations of pole position due to the interference of the 12-month annual and 14-month Chandler wobbles. The interference between those two closely spaced frequencies explains the 7-year beat period in the record that may be extracted by visual inspection. Of more interest in the present context is the slow drift of the pole relative to the Conventional International Origin (CIO), upon which these oscillatory variations are superimposed. The direction of drift is shown on the inset polar projection of Figure 2.3 by the arrow that points roughly along the 76 degree west meridian. The rate of drift in this direction is 0.95 ± (0.05) degree per million years (e.g., Dickman 1977). In 1952 Munk and Revelle published a paper that purported to show that this observed true polar wander required that some ongoing change in surface mass load of the planet be currently taking place. They suggested that the required surface load forcing was due to mass loss from Greenland and/or Antarctica. The theoretical analysis on which this conclusion was based was predicated on the assumption that insofar as the rotational response to surface loading was concerned the planet could be

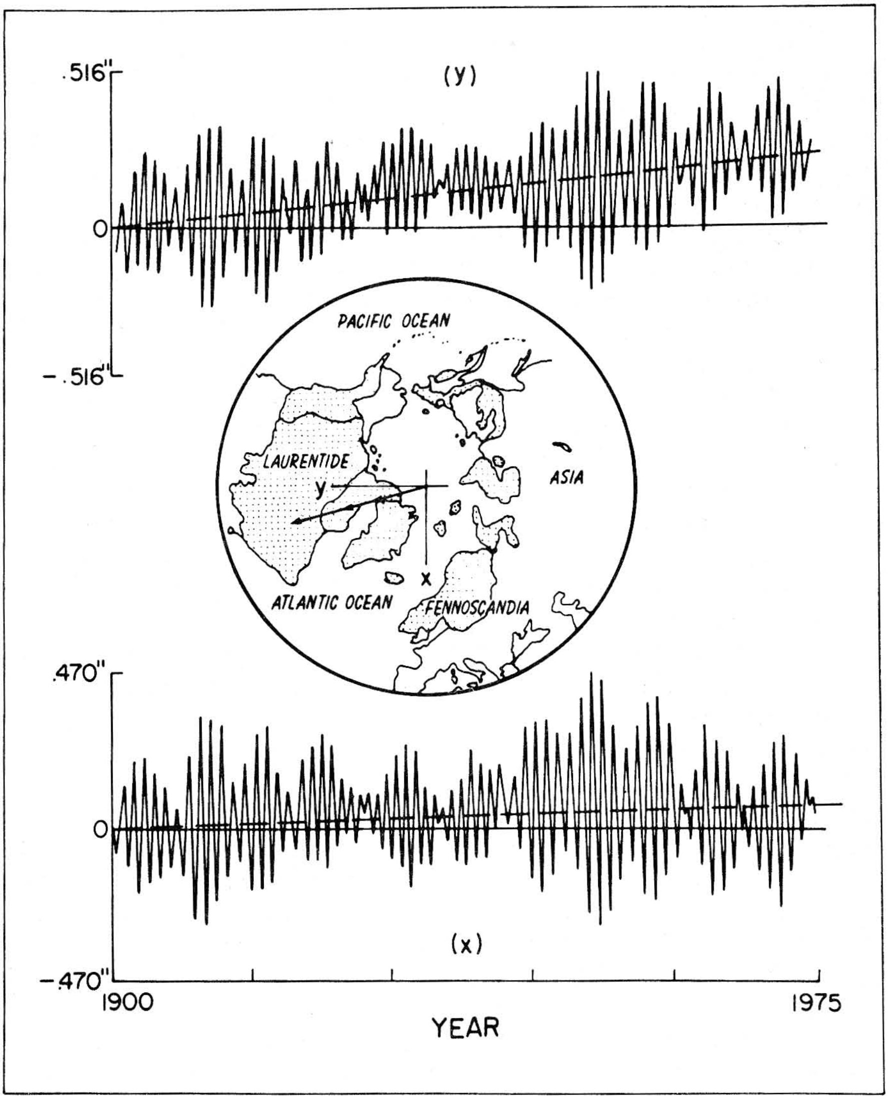

FIGURE 2.3 The ILS record of polar motion in the time period since 1900 relative to the conventional international origin (CIO).

assumed to be representable as a homogeneous viscoelastic sphere. A characteristic of the rotational response of such a model planet is that the centrifugal and isostatic adjustment contributions to the response exactly annihilate one another, the result being that no polar wander is predicted in circumstances in which the surface mass load is constant. To explain the drift observed in the pole path shown in Figure 2.3, Munk and Revelle were therefore obliged to invoke some time variation of surface load, and they pointed to the Greenland and/or Antarctic ice masses as being the likely cause. This idea has continued to play a role in the recent literature on sea level and climate change, where it is suggested as providing additional evidence that the mass of water in the global ocean must be increasing.

Unfortunately this analysis of Munk and Revelle (1952) has recently been shown to be incorrect. The flaw in their argument that the observed polar wander requires a concurrent variation of the surface mass load is that the argument is based on the assumption that the homogeneous viscoelastic model of the Earth is an adequate model in terms of which to describe the rotational response to surface mass loading. In a recent sequence of papers (Peltier 1982, Peltier and Wu 1983, Wu and Peltier 1984) it has been clearly demonstrated that the internal viscoelastic layering of the real Earth has an extremely important effect on the rotational response to surface loading. In fact the effect is such as to break the symmetry on the basis of which the centrifugal and isostatic adjustment contributions to the rotational response are forced to cancel one another at all times during free relaxation of the homogeneous model. Layered viscoelastic models therefore process a finite "memory" in their rotational response to surface loading such that the pole continues to wander long after the surface load has ceased to vary. In terms of such realistic viscoelastic models it is therefore conceivable that the polar wander illustrated on Figure 2.3 could simply be a memory of the planet's response to the last deglaciation event of the current ice age. That this could be the case is also strongly suggested by the fact that the direction of polar wander is slightly to the east of the centroid of the Laurentide ice mass, an effect that is an expected consequence of the additional forcing due to the deglaciation of Fennoscandia.

Analysis in the three previously cited papers shows in fact that the observed direction and rate of polar wander in the ILS path are both predicted very nicely on the basis of the assumption that the only rotational forcing is that due to the 10^5 year periodic ice age cycle that has dominated the $\delta^{18}O$ record of continental ice volume fluctuations during the past 700,000 years of Earth history. The polar wander speed predicted for a sequence of models that differ only in the complexity of their internal viscoelastic layering is shown in Figure 2.4. The zero of time on the figure is taken coincident with the end of the last 10^5 year glaciation cycle, of which seven have been included in the assumed prehistory. As discussed in Wu and Peltier (1984) the ice sheets on Canada, Fennoscandia, and West Antarctica have all been included and have been approximated by spherical caps of appropriate mass that accrete water from and discharge meltwater to, ocean basins of realistic form. The temporal history of each cap is assumed fixed by the sawtooth approximation to the typical $\delta^{18}O$ record shown on Figure 2.5. Following the zero of time on Figure 2.4 there is no further variation of surface load.

The models for which the polar wander-speed predictions are shown in Figure 2.4 consist of a homogeneous model with a lithospheric of thickness L = 120 km (fixed for all models as indicated on the figure) designated LOF (no core), a model with a homogeneous mantle and a high-density invisid core (LOF), a model with one density discontinuity in an otherwise homogeneous mantle (L1F), and a model with two internal mantle density discontinuities (L2F). The models with internal mantle density

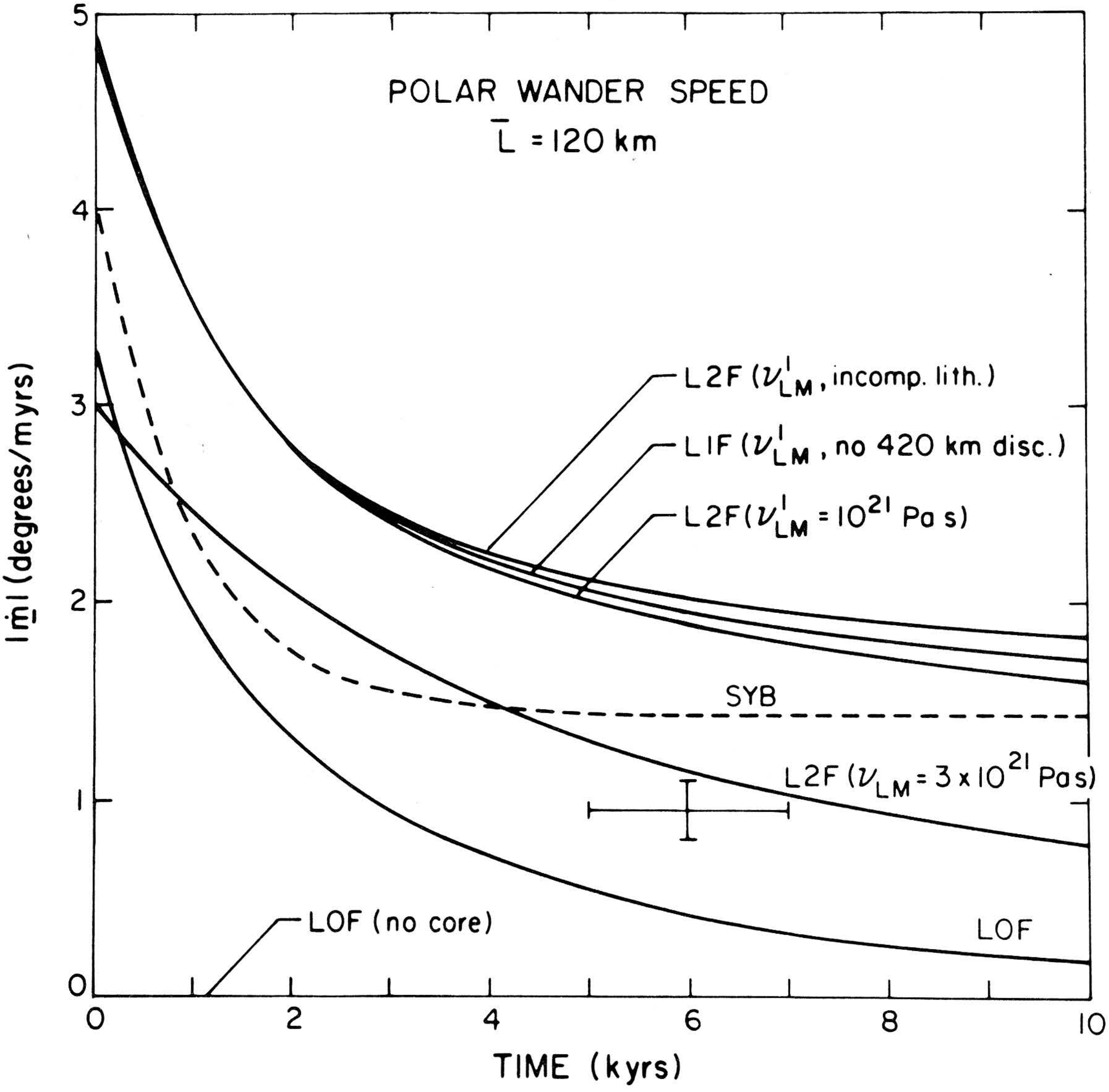

FIGURE 2.4 Polar wander-speed predictions for the viscoelastic models discussed in the text. The cross at t = 6 kyr is the observed secular drift extracted from the data shown in Figure 2.3.

discontinuities have these features located at 670-km depth (L1F) and 420-km depth (L2F). The magnitudes of the density contrasts in these models are close to those in the realistic model 1066B of Gilbert and Dziewonski (1975). Inspection of the various predictions shows first that essentially zero polar-wander speed is predicted for the homogeneous model (LOF no core) in accord with the analysis of Munk and Revelle (1952). However, as one adds structure to the interior of the model the speed prediction begins to depart very significantly from zero. The predictions are for models that have an upper-mantle viscosity of 10^{21} Pa s, and a good fit to the observations is clearly obtained by

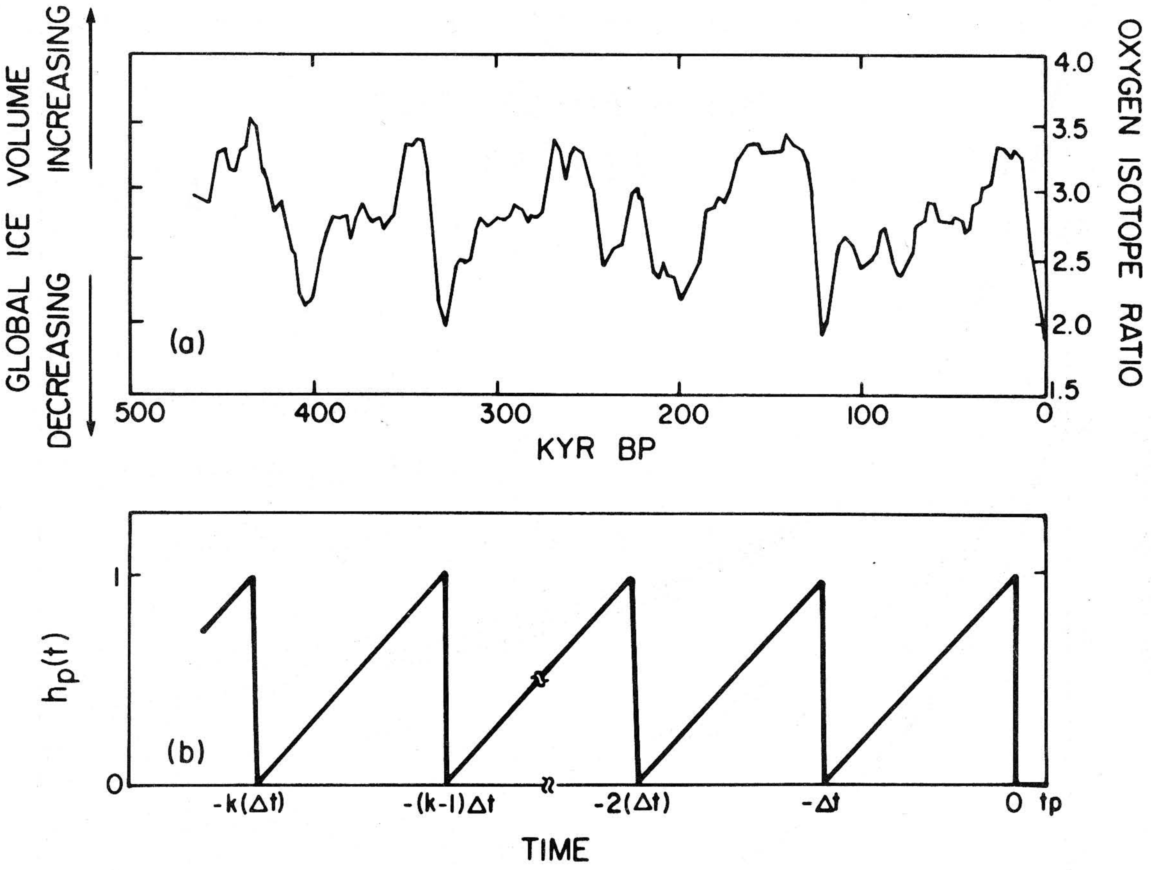

FIGURE 2.5 Sample $\delta^{18}O$ time series (upper) and sawtooth approximation (lower) employed to constrain the load cycle employed for the polar wander-speed predictions shown in Figure 2.4.

model L2F with a lower-mantle viscosity of 3×10^{21} Pa s. This same model has been shown to be compatible with most of the other data of glacial isostatic adjustment also. In particular, it has been shown to be compatible with the recently observed nontidal component of the acceleration of planetary rotation that has been extracted from the orbit of the LAGEOS satellite (Peltier 1983) and previously through the analysis of ancient eclipse data.

CONCLUSIONS

The influence of ongoing glacial isostatic adjustment in response to the melting of Würm-Wisconsin ice that began roughly 18,000 years ago and ended about 6000 years is a significant source of contamination of tide-gauge records of the variation of relative sea level. Before such data are invoked to constrain present-day variations of water volume, they should be decontaminated by removing isostatic adjustment effects using the gravitationally self-consistent model for rsl variations as a filter. An application of this technique to sea-level data from the

U.S. east coast shows that roughly 40 percent of the tide-gauge-inferred rsl rise is due to the glacial isostatic submergence of this coast. The residual could in principle be due either to an increase in the mass of water in the global ocean or to a steric effect.

The fact that the observed secular variations in the nontidal acceleration of planetary rotation and in the location of the rotation pole are both so well predicted on the basis of the assumption that no ongoing variation of surface mass load is occurring may be taken as strong evidence that the tide-gauge-inferred residual rate of rsl rise is predominantly steric in origin. These observations appear to be extremely sensitive to significant rates of change in the surface ice and water load. In fact, the two rotation effects are complimentary constraints in that the nontidal acceleration is particularly sensitive to ice melting near the rotation poles, whereas the polar wander is driven entirely by off-polar loading effects. Certainly the Munk and Revelle (1952) argument that the present-day observed polar wander requires a concurrent variation of surface-mass load is incorrect, however, since this is explicable on the basic of the hypothesis that it is entirely a consequence of previous load variations.

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