Twentieth century sea level: An enigma

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Changes in sea level (relative to the moving crust) are associated with changes in ocean volume (mostly thermal expansion) and in ocean mass (melting and continental storage): $\zeta(t) = \zeta_{\mathrm{steric}}(t) + \zeta_{\mathrm{eustatic}}(t)$. Recent compilations of global ocean temperatures by Levitus and coworkers are in accord with coupled ocean/atmosphere modeling of greenhouse warming; they yield an increase in 20th century ocean heat content by 2×10^{23} J (compared to 0.1×10^{23} J of atmospheric storage), which corresponds to $\zeta_{\mathrm{greenhouse}}(2000) = 3$ cm. The greenhouse-related rate is accelerating, with a present value $\dot{\zeta}_{\mathrm{greenhouse}}(2000) \approx 6$ cm/century. Tide records going back to the 19th century show no measurable acceleration throughout the late 19th and first half of the 20th century; we take $\dot{\zeta}_{\mathrm{historic}} = 18$ cm/century. The Intergovernmental Panel on Climate Change attributes about 6 cm/century to melting and other eustatic processes, leaving a residual of 12 cm of 20th century rise to be accounted for. The Levitus compilation has virtually foreclosed the attribution of the residual rise to ocean warming (notwithstanding our ignorance of the abyssal and Southern Oceans): the historic rise started too early, has too linear a trend, and is too large. Melting of polar ice sheets at the upper limit of the Intergovernmental Panel on Climate Change estimates could close the gap, but severe limits are imposed by the observed perturbations in Earth rotation. Among possible resolutions of the enigma are: a substantial reduction from traditional estimates (including ours) of 1.5–2 mm/y global sea level rise; a substantial increase in the estimates of 20th century ocean heat storage; and a substantial change in the interpretation of the astronomic record.

Fig. 1 defines the enigma. At the end of the ice age, global sea level was 125 m beneath the present level and rose rapidly to about −2 m by 5000 BC, but by 2000 BC, the rise had seized. Sea level relative to 1900 is designated by $\zeta(t)$. Following a recent monograph on sea level rise (1), we take a sustained *rate* of rise $\dot{\zeta}_{\mathrm{historic}}(t) \approx 18$ cm/century† (cm/cy) commencing in the late 19th century with no evidence of acceleration or deceleration until the mid-20th century (3). We refer to $\zeta_{\mathrm{historic}}(t)$ as distinct from the greenhouse warming-related $\zeta_{\mathrm{greenhouse}}(t)$ starting in the mid-20th century and accelerating rapidly. The greenhouse signal is in rough accord with the thermal expansion predicted by coupled ocean-atmosphere models (4–6) and is designated "steric" as distinct from "eustatic" (variation in global ocean mass). The historic signal has both steric and eustatic components. Measurements and models are consistent with $\zeta_{\mathrm{greenhouse}}(2000) = 2$–$3$ cm, hence

$$\zeta(2000) = \zeta_{\mathrm{historic}}(2000) + \zeta_{\mathrm{greenhouse}}(2000) = 18 + 3 = 21 \text{ cm}$$

for the 20th century sea level. The greenhouse *rate* of sea level rise has accelerated rapidly from $\dot{\zeta}_{\mathrm{greenhouse}}(1900) \leq 1$ cm/cy to $\dot{\zeta}_{\mathrm{greenhouse}}(2000) = 6$ cm/cy, giving

$$\dot{\zeta}(2000) = \dot{\zeta}_{\mathrm{historic}}(2000) + \dot{\zeta}_{\mathrm{greenhouse}}(2000)$$
$$= 18 + 6 = 24 \text{ cm/cy}$$

at the end of the century. The Intergovernmental Panel on Climate Change (IPCC) 2001 (2) "central estimate" for the eustatic contribution is 6 cm/cy, leaving a residual

$$\zeta - \zeta_{\mathrm{greenhouse}} - \zeta_{\mathrm{eustatic}} = 21 - 3 - 6 = 12 \text{ cm}$$

of 21 cm of 20th century rise unaccounted for. If steric, this residual rise would require 10^{24} J of 20th century incremental heat storage, far in excess of the measured and modeled 2×10^{23} J. If eustatic, this residual implies 40,000 gigatons of 20th century attrition of the polar ice sheet, well above the IPCC estimates and in conflict with certain astronomic measurements (as will be shown). Therein lies the enigma.

How could this enigma have been overlooked in such an intensely studied subject? It has not! Prior to the Levitus compilation (5), it was taken for granted by many of us that the residual historic rise would eventually be reconciled with thermal expansion as more information about ocean interior temperature became available. The authoritative IPCC 1990 chapter on sea level by Warrick and Oerlemans† refers to an "unexplained part" of past sea level rise starting in AD 1850. The IPCC 1995 report concludes that, "the rise in sea level has been due largely to the concurrent increase in global temperature over the last 100 years, . . . including thermal expansion of the ocean and melting of glaciers, ice caps and ice sheets." Recent progress in the documentation and understanding of interior ocean heat storage have served to sharpen the enigma. The favored interpretation in terms of thermal expansion is now difficult to reconcile with the observed dataset except possibly in the deepest ocean layers, where there are almost no systematic observations.

Sea Level During the Late Holocene Period

Estimates of the present *rate* of rise $\dot{\zeta}$ vary widely, from 10 to 25 cm/cy. There are three principal difficulties with estimating global sea level from the tide gauge records: (*i*) their limited duration, (*ii*) their clustered distribution, and (*iii*) the vertical movement of land to which they are attached. Extensive studies by Peltier (1, 7, 8) and Lambeck and coworker (9, 10) attribute the crustal movement to a viscous rebound of the solid Earth from removal of the ice load, with mantle material flowing from beneath the ocean toward regions previously glaciated. Because of the long relaxation times, the rebound process is still active even though deglaciation was virtually complete 4,000 years ago (see Fig. 1).

The recorded tide gauge record is written (TG, tide gauge)

$$\zeta_{\mathrm{TG}} = \zeta - \zeta_{\mathrm{rebound}}.$$

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Abbreviations: IPCC, Intergovernmental Panel on Climate Change; cy, century; lod, length of day.

See commentary on page 6524.

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†This is above the "central estimate" of 15 cm/cy in the latest assessment by the IPCC (2), but within their 10–20 cm/cy limits. We shall make frequent reference to IPCC 1990, 1992, 1995, and 2001.

‡The rebound effect reaches 100 cm/cy (!) in previously ice-covered regions. Rebound "correction" includes a significant redistribution of water mass associated with the gravitational potential of the rebound earth mass as well as the amplification by "self-gravitation" of the modified water mass (11, 12).

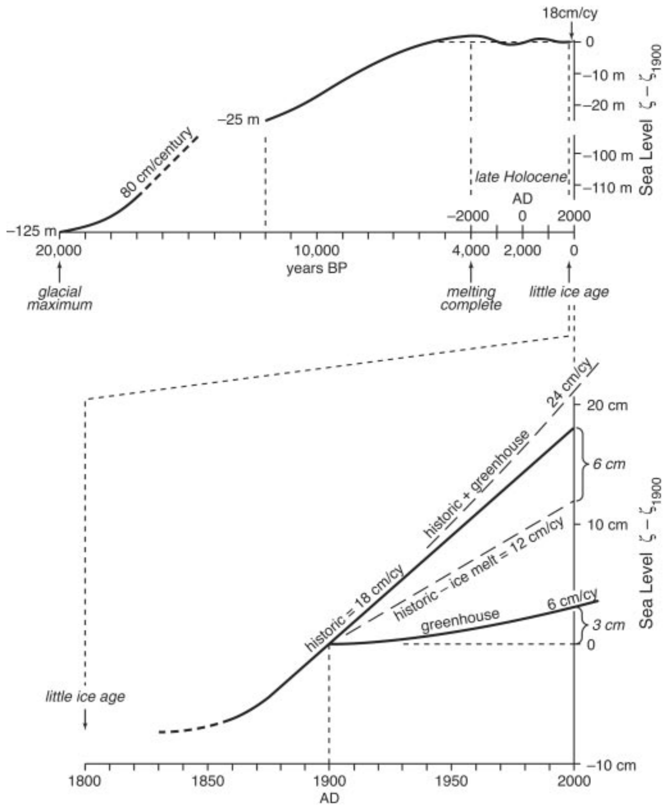

Fig. 1. Cartoon of the assumed model of holocene sea level (see text). After the glacial maximum 20,000 years ago, global sea level rose by 125 m and has been within a few meters of the present level since 4000 B.P. After the little ice age early in the 19th century, sea level rose at 18 cm/cy (the historic *rate*) with no measurable acceleration until the mid-20th century, when thermal expansion associated with greenhouse warming became significant, contributing an additional 3 cm by the year 2000. Greenhouse-related sea level rise has accelerated to the present *rate* of 6 cm/cy, making the historic + greenhouse *rate* 24 cm/cy.

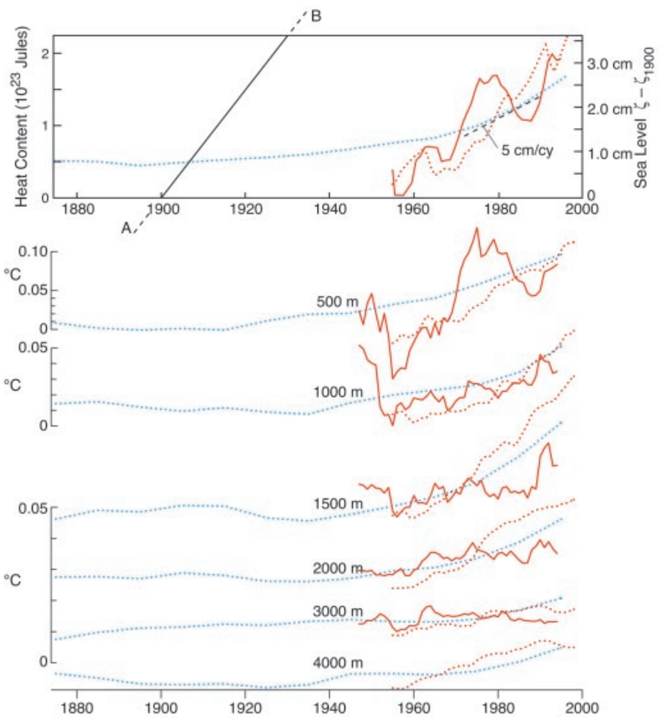

Fig. 2. (*Bottom*) Global mean temperature changes $\theta(t)$ at stated depths. Vertical scales are amplified at increasing depths in the ratio 1:2:4. (*Top*) Relative heat content $h(t)$. Solid red curves are *measured* temperatures [from *The World Ocean Atlas* (4, 5)] and associated heat content 0–3,000 m; dotted curves are model *predictions*; red from the Levitus *et al.* experiment GSSV (5) and blue from Barnett *et al.* (6). Parallel Coupled Model (PCM) decadal ensemble averaged (6). The scale (*top right*) gives the approximate sea level rise associated with the increased heat content. The line AB corresponds to a steric rise by 12 cm/cy.

The rebound corrections are large and lie between ±5 cm/cy in the "far field" of the former continental ice sheets.‡ By allowing for the rebound at individual tide gauges from geodynamic models, Peltier's (7) estimates of global sea level rise are modified from 17.1 ± 5.5 cm/cy to 18.4 ± 3.5 cm/cy, the important point being the reduction in the error bar. We return to the Peltier and Lambeck estimates in conjunction with the astronomic constraints.

Some of the rebound problems have been sidestepped by solving for sea level *acceleration* $\ddot{\zeta}(t)$, assuming that the crustal movements are of very low frequency. In an analysis of some 50 European tide gauges (Amsterdam, Stockholm, Brest, and Sheerness go back to 1700, 1774, 1797, and 1834, respectively), Woodworth (3) finds no evidence for an acceleration significantly different from zero for the late 19th to the mid-20th century.

The biased distribution of the gauges poses a serious problem to estimating a global mean. Application of empirical orthogonal functions avoids some of the undue emphasis on closely clustered stations (13, 14). Peltier (1) combined some key 25 stations into 10 station clusters. An important development is the application of satellite altimetry (15), which yields a global estimate $\dot{\zeta} = 25 \pm 13$ cm/cy for the period 1993–1998. Near-global satellite coverage avoids the gauge distribution problem and reduces the role of land movement to a consideration of the gravitationally induced redistribution of water mass‡ and of the relative movement of the global-mean seafloor (not negligible). The global coverage will eventually make satellite altimetry the method of choice; for the time being, the record is too short to permit extrapolation to century-scale sea level.

In an important paper, Cabanes *et al.* (16) demonstrate that the Douglas-Peltier estimate is biased by a concentration of tide stations in regions of recent warming. A radical downward revision of the global mean rise would go a long way toward resolving the enigma. But regional temperature changes are associated with decadal and multidecadal processes that we believe to be distinct from those that govern sea level on a century time scale. It remains to be demonstrated that a warming bias has contaminated the estimates derived from late 19th and early 20th century records (3). We have taken a traditional $\dot{\zeta} = 18$ cm/cy for the 20th century preindustrial sea level rise.

Warming and Freshening of the Oceans

Fig. 2 shows a compilation of ocean warming from the *World Ocean Database* of five million temperature profiles (4, 5). Ocean heat storage has increased by 2×10^{23} J since the mid-1950s, corresponding to an average heat flux of 0.3 W/m^2 (compared to 2 W/m^2 for greenhouse warming and 0.08 W/m^2 geothermal heat flux through the sea floor). The record is dominated by decadal-scale oscillations (partly predicted by the Levitus model) that imply heat-flux perturbations of order 1 W/m^2 accompanied by ±1-cm steric sea level oscillations; the large perturbations make it difficult to deduce century-scale trends. Warming

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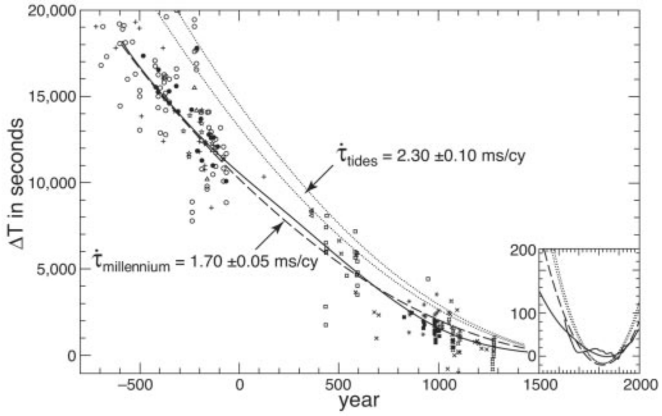

Fig. 3. The time difference ΔT derived from Babylonian, Chinese, Arabic, and Greek eclipses (18). The best-fitting parabola (dashed) is consistent with an increase in the length of day by 1.70 ± 0.05 ms/cy over the last 2,700 years. The solid curve is fitted by using cubic splines. The parabola associated with tidal friction (19) is represented by the $\pm 1\sigma$ limits (dotted). The *Inset* shows the situation for the last 500 years with $\times 25$ amplification.

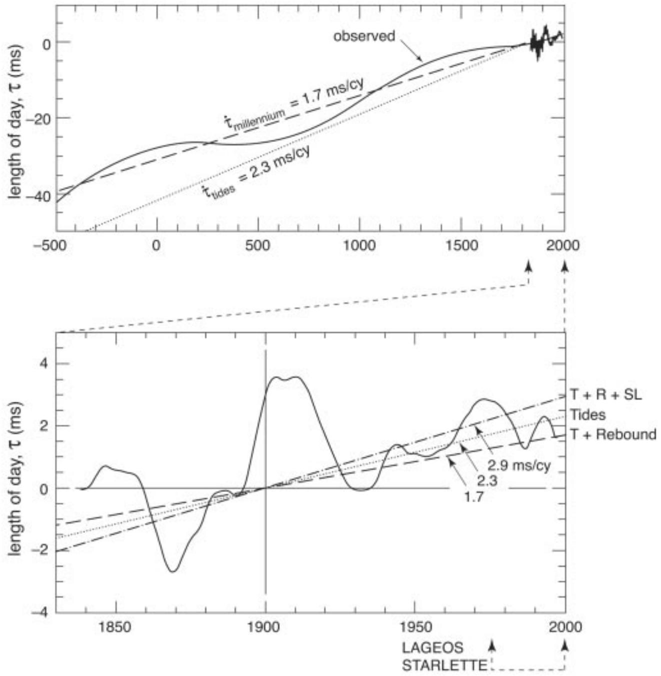

Fig. 4. Length of day, τ in milliseconds relative to 1900 (18, 19). The long-term observed rate 500 BC to AD 1990 is $\dot{\tau}_{\text{millennium}} = +1.7$ ms/cy. Tidal deceleration is associated with $\dot{\tau}_{\text{tides}} = +2.3$ ms/cy, indicating a long-term residual $\dot{\tau}_{\text{rebound}} = -0.6$ ms/cy associated with a viscous rebound of the solid Earth from a removal of the ice sheets. (*Bottom*) $\tau(t)$ for the last 170 years on an enlarged scale, together with the previously established linear trends: $\dot{\tau}_{\text{tides}} = +2.3$ ms/cy, $\dot{\tau}_{\text{tides}} + \dot{\tau}_{\text{rebound}} = 2.3 - 0.6 = 1.7$ ms/cy, and $\dot{\tau}_{\text{tides}} + \dot{\tau}_{\text{rebound}} + \dot{\tau}_{\text{sealevel}} = 1.7 + 1.2 = 2.9$ ms/cy for a 12 cm/cy eustatic rise in sea level.

is dominantly in the upper 1,000 m. The quite separate models[§] of Levitus and Barnett (4, 6) both overpredict deep ocean warming but are in rough agreement with regard to the total heat content. A plot of the computed steric sea level (right scale) does not differ appreciably from that of heat content, corresponding to a "climate-effective coefficient of thermal expansion" of 1.29×10^{-4}·°C^{-1}. (We ignore a small but significant halosteric contribution.)

The Levitus compilation does not include a considerable warming early in the century (evidently not controlled by greenhouse gases). Data in the southern hemisphere are sparse, and the abyssal ocean is omitted from the compilation. For warming on a century time scale or longer, the warming of the deep ocean contributes about twice as much to sea level rise as thermocline warming (17). Still, the situation is hard to reconcile with the heat flux required to account for residual sea level rise $\dot{\zeta} = 12$ cm/cy (AB in Fig. 2 extended throughout the century).

We are left with a eustatic interpretation of the residual sea level. Here the situation presented by the authoritative IPCC 2001 report is not promising. Terrestrial storage (reservoirs − groundwater = $-6 + 4 = -2$ cm/cy equivalent sea level) almost cancels glacial melting (+3 cm/cy), giving essentially a net zero 20th century contribution with very wide error limits, −9 to +8 cm/cy. For Greenland and Antarctica, the estimates are 0.5 ± 0.5 and 1 ± 1 cm/cy, respectively. We now turn to some integral constraints associated with the overall angular momentum balance of the planet.

Astronomic Constraints

In a remarkable compilation, Stephenson and Morrison (18) have now brought modern observations into accord with solar and lunar eclipses in Babylon, China, Europe, and the Arab world. The parabola marked $\dot{\tau}_{\text{millennium}}$ in Fig. 3 shows the amount the Earth is off as a timekeeper, 5 h in 2,500 years. The (constant) curvature is proportional to the mean change in the length of day (lod), $\dot{\tau} = 1.70 \pm 0.05$ milliseconds/century (ms/cy). The contribution to $\dot{\tau}$ from tidal friction can be independently derived from the requirement that the total angular momentum of the Earth–Moon system be conserved [the best estimates now come from lunar laser ranging (19)]. Surprisingly, the tidal effect *exceeds* the total measured change, leaving

$$\dot{\tau}_{\text{millennium}} - \dot{\tau}_{\text{tide}} = 1.7 - 2.3 = -0.6 \text{ ms/cy}$$

to be accounted for.

The residual spin-up (negative $\dot{\tau}$) is attributed to the decrease in the Earth's moment of inertia associated with the postglacial flow *toward* the polar regions previously glaciated. Peltier (7) finds that the same geodynamic model that produced sensible corrections at individual tide gauges (and agrees with other geodetic measurements) is consistent with $\dot{\tau}_{\text{rebound}} = -0.6$ ms/cy.

The eustatic sea level rise from melting of polar ice sheets is associated with a movement of water mass *away* from polar regions and so is opposite to the earth rebound. A eustatic global rise by 1 cm is associated with an increase in the lod by 0.1 ms. If a residual rise by 12 cm/cy were to be attributed to high-latitude melting, then

$$\begin{aligned}\dot{\tau}_{\text{millennium}} &= \dot{\tau}_{\text{tide}} + \dot{\tau}_{\text{rebound}} + \dot{\tau}_{\text{sealevel}} \\ &= 2.3 - 0.6 + 1.2 = 2.9 \text{ ms/cy}\end{aligned}$$

would lie *above* the curve for $\dot{\tau}_{\text{tide}}$ by the amount it is observed to lie beneath (see Fig. 3).

Higher resolution in modern measurements (20) shows decadal-scale excursions superposed on the mean trend (Fig. 4). The short-period oscillations bear some resemblance to the steric oscillations in Fig. 2. This is not an accident; the warm El Niño Southern Oscillation (ENSO) events (with a positive steric sea

§We have just received the results of a third independent model study by B. Reichert, R. Schnur, and L. Bengtsson (Max-Planck-Institut für Meteorologie Report 327, August 2001). For the period 1955–1994 in the upper 3,000 m, they estimate 2.3×10^{23} J, consistent with what is expected from anthropogenically forced Global Circulation Model (GCM) integrations.

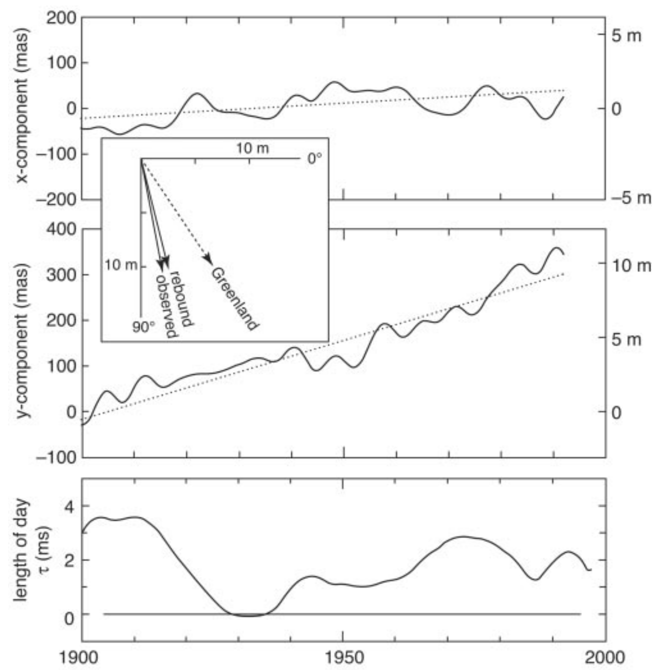

Fig. 5. Motion of the pole of rotation in milliarcseconds (mas) and in meters; x toward Greenwich and y toward 90° west of Greenwich (27, 28). The mean observed motion (dotted), together with that computed by Peltier (7) for rebound, is shown in *Inset.* The dashed arrow toward Greenland is the computed displacement for 12-cm eustatic sea level rise associated with Greenland melting. Changes in the length of day over the same interval are taken from Fig. 4.

level signature of negligible rotational consequence) are accompanied by westerly wind anomalies and an excess in atmospheric angular momentum consistent with the observed changes in the lod (21, 22). The high-frequency "noise" masks the mean trend, and it is impossible on the basis of the modern observations alone to distinguish between 1.7 and 2.9 ms/cy (0 or 12 cm/cy eustatic rise).

A *direct* measure of the Earth's moment of inertia has been derived from the acceleration of the nodes of low-orbit satellites (23, 24), yielding $\dot{\tau}_{\text{inertia}} = -0.6$ ms/cy (Lageos I) to -0.38 ms/cy (Starlette) for the last few decades, in remarkable accord with the previously cited astronomic observations.

Polar Motion

An independent rotational constraint comes from the polar motion. For a slow (compared to the Chandler wobble of 14 mo) global eustatic rise from a concentrated source, the pole of rotation responds by moving toward the melting source and thus maximizing the equatorial oblateness. ["Polar wander" was formulated in 1887 by George Darwin (son of Charles) in the geologic context.] These considerations offer the intriguing possibility of distinguishing between a somewhat off-axis source (Greenland) and a nearly on-axis source (Antarctica). Early attempts were limited by the available astronomic data (25, 26). During the last hundred years (27, 28), the north pole of rotation has wandered 10.81 ± 0.03 m towards $79.2° \pm 0.2°$W (Fig. 5). The same geodynamic model that produced $\dot{\tau}_{\text{rebound}} = -0.6$ ms/cy is found to be consistent with the polar motion (7, 8).

Triple Accord

We note the remarkable accord of three independent lines of investigation: (*i*) millennium eclipse data (18) plus lunar laser ranging (19) yields $\dot{\tau}_{\text{millennium}} - \dot{\tau}_{\text{tide}} = 1.7 - 2.3 = -0.6$ ms/cy. (*ii*) Acceleration of the nodes of low-orbit satellites (23, 24) yields $\dot{\tau}_{\text{inertia}} = -0.4$ to -0.6 ms/cy for the last few decades. (*iii*) Postglacial rebound is of the right magnitude and can be "tuned" to yield $\dot{\tau}_{\text{rebound}} = -0.6$ ms/cy by setting the deep-mantle viscosity to $10^{21.4}$ Pa s (Table 1), but this same Earth model then accounts for the measured polar wander of 10 m/cy towards 75°W [or vice versa, by first fitting to the polar wander, Peltier (7, 8, 29, 30) independently derives $\dot{\tau}_{\text{rebound}} = -0.6$ ms/cy]. Lambeck and Johnson (9, 10), using a quite different earth viscosity model, estimate $\dot{\tau}_{\text{rebound}} = -0.47$ ms/cy. With $\dot{\tau}_{\text{inertia}} \approx \dot{\tau}_{\text{rebound}}$, we have a pleasing triple accord; the trouble is that this leaves little room for an eustatic rise in sea level.

We now attempt to quantify this statement by examining the implications of an assumed rise $\dot{\zeta}_{\text{eustatic}} = 0, 5, 10$, and 15 cm/cy (Table 1).[¶] To what extent have the geodynamic models been "tuned" to support the pure rebound hypothesis? An increase in lower mantle viscosity is associated with a longer relaxation time and a larger remaining modern rebound from the deglaciation after the last glacial maximum. The result is a larger (more negative) d inertia$/dt$ and d lod$/dt$ to compensate for the eustatic rise in sea level.

Take $\dot{\zeta}_{\text{eustatic}} = 10$ cm/cy and so (using Peltier's log-viscosity of 21.4) $\dot{\tau}_{\text{inertia}} = \dot{\tau}_{\text{rebound}} + \dot{\tau}_{\text{eustatic}} = -0.6 + 1.0 = +0.4$ ms/cy (Table 1), in disagreement with -0.6 ms/cy from *i* and *ii.* Peltier (figure 31 of ref. 7) demonstrates that if the lower mantle log-viscosity is increased from 21.4 to 21.7 and accordingly $\dot{\tau}_{\text{rebound}}$ changed from -0.6 to -1.6 ms/cy, we can bring $\dot{\tau}_{\text{inertia}} = \dot{\tau}_{\text{rebound}} + \dot{\tau}_{\text{eustatic}} = -1.6 + 1.0 = -0.6$ ms/cy, into agreement with *i* and *ii.* Similarly, Lambeck can maintain the triple accord by raising the log-viscosity estimate from 21.1 to 21.8 to obtain $\dot{\tau}_{\text{inertia}} = -1.43 + 1.0 = -0.43$ ms/cy. The trouble is that the larger rebound leads to a larger-than-observed polar wander and that *i* then implies a history of ancient sea level that is not in accord with the evidence [the reader is referred to the treatise by Peltier (7) for further discussion].

With regard to the polar wander, the Peltier and Lambeck estimates are in rough accord for the case of zero sea level rise: a movement of order 10 m/cy toward the North Atlantic, as observed. Again taking the case of a 10 cm/cy eustatic rise from melting of the Greenland ice sheet, the resultant movement by 10 m in the direction of Greenland added vectorially to the Peltier rebound yields a total displacement by 18.7 m toward 60°W, significantly larger than the observed wander.[‖]

The simplest interpretation of the overall rotational evidence is that eustatic sea level rise is less than 5 cm/cy and so a minor contributor towards $\tau_{\text{millennium}}(t)$. However, a larger-than-assumed melting of continental glaciers and other midlatitude sources is subject to weaker rotational constraints.

Circular Argument?

Could the triple accord be a cruel accident?**

In the present context, as observations of higher resolution have become available, we note that the record mean trend $\langle\dot{\zeta}\rangle$ (or any of its proxies; Figs. 2–5) is greatly exceeded by rms$(\dot{\zeta})$ associated with the high-frequency oscillations. (This is the expected result for time series with a red ζ spectrum and a violet $\dot{\zeta}$ spectrum.) Accordingly, the high-frequency "noise" of

[¶]The oblateness J_2 is the amplitude of the degree 2 axial harmonic in the spherical harmonic expansion of the gravitational potential. The fractional change in the length of day is given by $\dot{\tau}/\tau = \ + 2\dot{J}_2$. Some authors use $c_{20} = 5^{-1/2}J_2$. Equivalent units of polar motion are 1 m/cy = 0.090° latitude/My = 0.32 milliarcseconds/y.

[‖]We ignore polar wander from melting on the more axis-symmetric Antarctic. It is surprising that rebound (with mass movement toward previously glaciated areas) and present sea level rise (movement away from glaciated areas) are not more orthogonal, as they are for lod estimates. We do not understand the successive eastward displacement of the Lambeck vectors.

**It would not be the first time that an agreement in the subject of Earth rotation has dissolved in the light of subsequent observations (ref. 26, p. 187).

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Table 1. Parameters of rotational constraint on estimates of sea level rise

$\dot{\zeta}$ cm/cy	0			5		10		15		Observed
Peltier parameters (7)										
log (η Pa s)	*21.3*	21.4	*21.5*	21.4		21.4		21.4		
$\dot{J}_2$ 10^{-11}·yr^{-1}	*−2.5*	−3.0	*−3.5*							
$\dot{\tau}_{\mathrm{inertia}}$ ms/cy	*−0.43*	−0.51	*−0.60*	−0.10		+0.40		+0.90		−0.39 to −0.60
Polar motion				A	G	A	G	A	G	
$\lvert\dot{m}\rvert$ m/cy	*10.5*	9.4	*8.3*	9.4	13.9	9.4	18.7	9.4	23.5	9.9–10.2
toward		76°W		76°W	65°W	76°W	60°W	76°W	57°W	66–75°W
Johnson and Lambeck parameters (10)										
$\dot{c}_{20}$ 10^{-19}·s^{-1}	*2.8*	3.5	*4.2*	3.5		3.5		3.5		3.2 to 5
$\dot{J}_2$ 10^{-11}·yr^{-1}	*−2.0*	−2.5	*−3.0*	−2.5		−2.5		−2.5		
$\dot{\tau}_{\mathrm{inertia}}$ ms/cy	*−0.34*	−0.43	*−0.51*	−0.43		−0.43		−0.43		−0.39 to −0.60
log (η Pa s)	*21.0*	21.1	*21.2*	21.4		21.8		22.2		
Polar motion				A	G	A	G	A	G	
$\lvert\dot{m}\rvert$ m/cy	*18*	16.5	*15*	10.6	8.8	12.5	10.3	10.9	15.0	9.9–10.2
toward	*63°W*	62.5°W	*62°W*	78°W	48°W	75°W	21°W	72°W	8°E	66–75°W

The four main columns correspond to an assumed rise in sea level by $\dot{\zeta}$ = 0 (rebound only), 5, 10, and 15 cm/cy, respectively, for A, Antarctic and G, Greenland melting. The side columns (*italics*) for $\dot{\zeta}$ = 0 show the sensitivity to $\dot{J}_2$ (figure 30 of ref. 7, figure 11 of ref. 10). Johnson and Lambeck assume a fixed value of $\dot{c}_{20}$ = 3.9×10^{-9}·s^{-1} (and the associated values $\dot{J}_2 = -2.5 \times 10^{-11}$·yr^{-1} and $\dot{\tau} = -0.043$ ms/cy), yielding the stated deep-mantle log viscosities (figure 12 of ref. 10) and polar motion (figure 13 of ref. 10).

a long time series becomes the "signal" in a shorter time series of higher resolution. For the millennium record (Fig. 3 *Upper*)

$$\dot{\tau}_{\mathrm{millennium}} = \dot{\tau}_{\mathrm{tide}} + \dot{\tau}_{\mathrm{rebound}} + \dot{\tau}_{\mathrm{sealevel}}$$

$$= 2.3 - 0.6 \pm 1.5 = 1.7 \pm 1.5 \text{ ms/cy},$$

where $\dot{\tau}_{\mathrm{sealevel}} = \pm 1.5$ ms/cy is associated with the temporary spline fits (solid curve) that fluctuate about the mean parabola. (Here we have attributed the signal-to-tidal friction and postglacial rebound and the ±1.5 ms/cy noise to sea level; the latter is pure speculation.) If we were to attribute the residual $\dot{\zeta} = 12$ cm/cy to the melting of polar ice sheets, then

$$\dot{\tau}_{\mathrm{century}} = \langle \dot{\tau}_{\mathrm{millennium}} \rangle + \dot{\tau}_{\mathrm{sealevel}} + \dot{\tau}_{\mathrm{decade}}$$

$$= 1.7 + 1.2 \pm 11 = 2.9 \pm 11 \text{ ms/cy}.$$

The decadal "noise" involves coupled variations in the distributions of temperature, mass, and velocity (21, 22) and so is manifested in the steric sea level, moments of inertia, and the Earth's variable rotation. The important thing here is that the variability of ±11 ms/cy greatly exceeds the postulated century mean trend of 2.9 ms/cy, and that a variable $\dot{\tau}_{\mathrm{century}}(t)$ will occasionally equal $\dot{\tau}_{\mathrm{millennium}} = 1.7$ ms/cy. This implies that the present measured $\dot{J}_2$ near -3.5×10^{-11} y^{-1} (associated with $\dot{\tau}_{\mathrm{rebound}} + \dot{\tau}_{\mathrm{sealevel}} = -0.6 + 0 = -0.6$ ms/cy) might be a temporary (and cruel) accident and that, over the next century, we can expect on average $\dot{J}_2$ of order $+3 \times 10^{-11}$ y^{-1} ($\dot{\tau}_{\mathrm{rebound}} + \dot{\tau}_{\mathrm{sealevel}} = -0.6 + 1.2 = +0.6$ ms/cy). These numbers would be consistent with a traditional sea level rise, still leaving intact a pleasing *dual* accord between the astronomically and geodetically derived estimates of millennium rebound.

Discussion

This paper does little toward solving the problems of the historical rise in sea level. In looking for causes, I have applied what Edward Bullard (31) has called the "Sherlock Holmes procedure" of eliminating one suspect after another. The procedure has left us without any good suspect (it is a matter of *attribution*, not of error bars), but I am reluctant to accept large error bars as definitive evidence for dismissing the traditional estimates of 1.5–2 mm/y for the 20th century sea level rise.

Thermal expansion was the candidate of choice at the time of the first IPCC review. This choice has been almost foreclosed as a major factor by the recent compilations of Levitus and by recent model calculations that account for the incremental ocean heat storage as a consequence of greenhouse warming. The computed steric rise is too little, too late, and too linear.

The rotational evidence, although convoluted, appears to rule out a large eustatic contribution from melting on Antarctica and Greenland, assuming that the measured $\dot{J}_2$ is representative of the 20th century. However, an enhanced contribution from glacial melting and other midlatitude sources is NOT ruled out by the rotational evidence.

Cabanes *et al.* (16) have demonstrated that the historical estimates of $\dot{\zeta}$ (here taken at 18 cm/cy) are severely biased by a concentration of tide stations in areas of recent warming, and that global estimates have to be radically revised downward. It remains to be demonstrated whether this bias extends to the traditional estimates for the rise in sea level on a century time scale.

Among the many possibilities for resolving the enigma, we suggest the following:

- Traditional estimates of the combined (steric plus eustatic) sea level rise (in the range 1.5–2 mm/y) are much too high [the Cabanes *et al.* (16) view];
- Levitus estimates of ocean heat storage and the associated steric rise are much too low;
- rotational bounds on the eustatic rise are not valid (see text);
- generous error bars in all these estimates mask the enigma (IPCC);
- all of the above;
- none of the above.

Sea level is important as a metric for climate change as well as in its own right. We are in the uncomfortable position of extrapolating into the next century without understanding the last.

I have had the benefit of discussion (but not necessarily agreement) with many people: T. Barnett, A. Cazenave, J. Dickey, K. Hasselmann, S. Levitus, R. Peltier, and C. Wunsch. I hold the Secretary of the Navy Research Chair in Oceanography.

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