GRACE era secular trends in Earth rotation parameters: A global scale impact of the global warming process?

Keven Roy[1] and W. R. Peltier[1]

Received 25 February 2011; revised 5 April 2011; accepted 11 April 2011; published 24 May 2011.

[1] Recent trends in the two primary anomalies in the rotational state of the planet are analyzed in detail, namely those associated with the speed and direction of polar wander and with the non-tidal acceleration of the rate of axial rotation (via the measurement of the changing oblateness of the Earth's shape). It is demonstrated that a significant change in the secular trends in both of these independent parameters became evident subsequent to approximately 1992. It is suggested that both parameters might have come to be substantially influenced by mass loss from both the great polar ice sheets, and from the very large number of small ice-sheets and glaciers that are also being influenced by the global warming phenomenon. The modern values for the secular drifts in those parameters that we estimate are appropriate to the period during which measurements have been made by the satellites of the Gravity Recovery and Climate Experiment (GRACE). These changes in secular rates might greatly assist in understanding why the GRACE-inferred values of the time derivatives of the degree two and order one Stokes coefficients differ so significantly from those associated with Late Quaternary ice-age influence. **Citation:** Roy, K., and W. R. Peltier (2011), GRACE era secular trends in Earth rotation parameters: A global scale impact of the global warming process?, *Geophys. Res. Lett.*, *38*, L10306, doi:10.1029/2011GL047282.

1. Introduction

[2] For at least a century, the rotational state of the planet has been known to display variability on timescales varying from daily to the multi-million year timescale on which mantle convection processes and lunar tidal interactions become prominent [*Peltier*, 2007]. In particular, variability in the Earth's rotational state is most usefully expressed in terms of variations in the position of its rotation axis with respect to a body-fixed frame of reference (usually referred to as true polar wander), and in terms of changes in the rate of planetary rotation about the instantaneous axis of rotation, resulting in changes in the length of the day. Short-timescale variations in the length of the day have been shown to be caused by angular momentum exchanges between the Earth and its atmosphere [*Hide et al.*, 1980], while the El Niño – Southern Oscillation (ENSO) phenomenon has been identified as a major source of its interannual variability [*Cox and Chao*, 2002; *Dickey et al.*, 2002]. On annual timescales, the position of the rotation axis varies primarily due to the seasonal exchange of atmospheric mass between the Northern and Southern hemispheres, and with a period of approximately 14 months because of the Chandler wobble, a phenomenon primarily caused by pressure changes on the ocean floor [*Gross*, 2000]. However, beyond these short timescale processes, secular variations are clearly present in both rotational observables, and they have been associated with the lasting influence of ice ages via the Glacial Isostatic Adjustment (GIA) process [e.g., *Peltier*, 1982; *Wu and Peltier*, 1984]. Our purpose in the present paper is to demonstrate that the secular rates of change of both properties of the rotational state began to depart significantly, subsequent to the early 1990s, from rates that had remained approximately fixed for a timescale of the order of centuries.

2. Earth Rotation and the Late Quaternary Ice-Age

[3] Mathematical models of the GIA process began to be developed in the 1970s [*Peltier*, 1974; *Peltier and Andrews*, 1976; *Peltier*, 1976; *Farrell and Clark*, 1976; *Clark et al.*, 1978; *Peltier et al.*, 1978], and among the most recent versions of these, the ICE-5G (VM2) model [*Peltier*, 2004], has been successfully used to predict the impact of ice-age influence on the rotational state of the planet. This influence is characterized via the true polar wander phenomenon, and via the J_2 coefficient of the spherical harmonic expansion of the gravitational potential field of the planet, which provides a measure of the non-tidal acceleration of the planetary rate of rotation.

[4] The signal associated with true polar wander has been studied since the end of the 19th century with the continuous record of the International Latitude Service (ILS) until approximately 1980 [*Yumi and Yokoyama*, 1980], and with the subsequent use of star catalogues like Hipparcos in the space era. A further influence of true polar wander is recorded in Earth Orientation Parameters (EOPs). These parameters provide the precise transformation between the International Terrestrial Reference System (ITRS) and its celestial counterpart, and are determined by a set of independent space-geodetic techniques, which include very long baseline interferometry (VLBI), global positioning system (GPS) measurements, as well as lunar and satellite laser ranging (SLR) [*Ratcliff and Gross*, 2010]. The combination of these independent signals provides an unbiased measure of polar motion since the mid-1970s [*Ratcliff and Gross*, 2010]. Beyond the existence of the periodic and quasi-periodic signals in polar motion, *Gross and Vondrák* [1999] inferred the existence of a secular trend in the ILS and Hipparcos polar motion series, as well as in the space-geodetic measurements, with their preferred estimate of this trend inferred to be 3.51 (±0.01) mas/yr (milliarcseconds/year), towards 79.2 (±0.20)°W longitude, modified to a rate of 4.03 mas/yr

[1]Department of Physics, University of Toronto, Toronto, Ontario, Canada.

0094-8276/11/2011GL047282

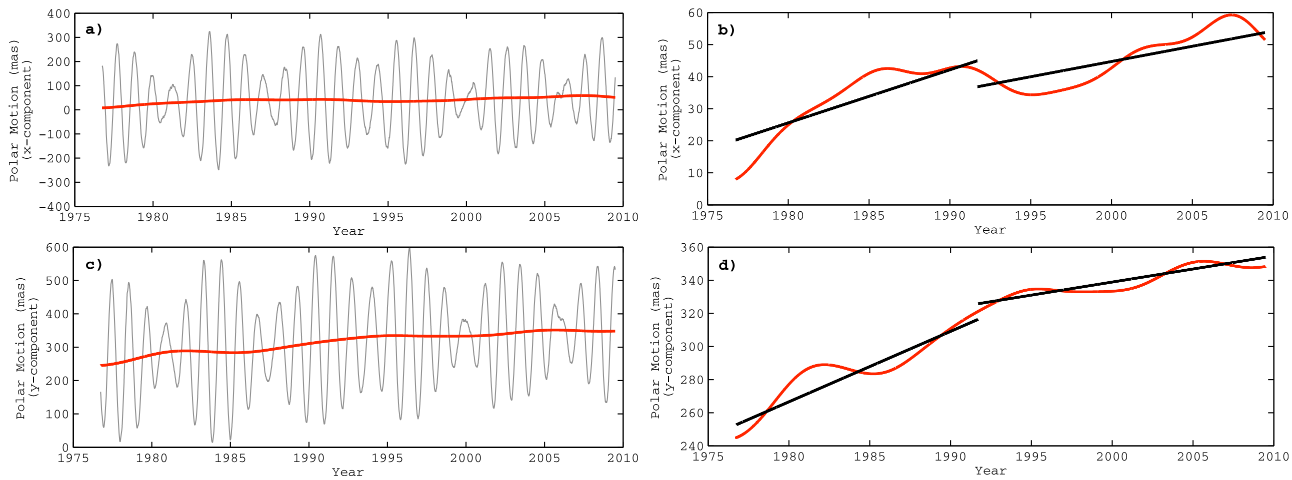

Figure 1. Study of the polar wander from the SPACE2008 data set [*Ratcliff and Gross*, 2010]. (a, b) Raw x-component of polar wander (dark grey), its subjection to a 6-yr, low-pass, Butterworth filter (red), and the two linear fits for the time periods 1976–1992 (rate: 1.7 mas/yr), and 1992–2009 (rate: 0.9 mas/yr). (c, d) Raw y-component of polar wander (dark grey), its subjection to a 6-yr, low-pass, Butterworth filter (red), and the two linear fits for the time periods 1976–1992 (rate: 4.1 mas/yr), and 1992–2009 (rate: 1.5 mas/yr).

towards 68.4°W longitude if corrected to the hotspot frame of reference [*Argus and Gross*, 2004].

[5] In comparison, variations in the length of the day over historical periods of time have been studied through the analysis of past lunar and solar eclipses [*Stephenson and Morrison*, 1995]. Taking into account the tidal braking of the Earth's spin, which is known from precise laser ranging observations of the recession of the Moon, *Stephenson and Morrison* [1995] inferred an average non-tidal acceleration of 1.6 (±0.4) × 10^{-22} rad s^{-2}, which corresponds to a rate of change in the oblateness of the Earth, as measured by J_2, of −3.5 (±0.8) × 10^{-11} yr^{-1}. The advent of the space age also enabled the precise study of the Earth's gravitational field, in particular through the analysis of variations existing in its zonal components, which are tightly connected to the rotational rate of the planet [*Yoder et al.*, 1983]. *Peltier* [1983] demonstrated this effect to be explicable in terms of the glacial isostatic adjustment process. Using the satellite laser ranging (SLR) technique for tracking the orbits of geodetic satellites, a measurement of the time rate of change of the oblateness of the Earth is obtained, which enables the study of large mass redistributions in the system. Using the SLR data from seven satellites, *Cheng and Tapley* [2004] studied the variation of the J_2 component over a 28-year period. This analysis enabled them to establish the existence of strong ENSO-induced interannual variations over timescales of 4 to 6 years, and led them to the inference of a long-term variation with a period of around 21 years. The existence of a secular trend in the signal was also demonstrated, and estimated to have a value of approximately −2.75 × 10^{-11} yr^{-1}, consistent, within the error bounds, with the earlier estimate based upon the analysis of the timing of ancient eclipses by *Stephenson and Morrison* [1995].

[6] Recent changes in the polar motion observable have been noticed, and a possible kink in its secular trend was suggested to have begun in the mid-1990s [*Gross and Poutanen*, 2009], while studies of the Earth's dynamic oblateness (J_2) have also pointed towards a recent change in its secular trend [*Cox and Chao*, 2002]. However, no simultaneous study of these two observables has ever been attempted. We show in what follows that both observables began to depart from their previously established, Late Quaternary ice-age related, GIA-controlled trends, at a somewhat earlier time. The simultaneity of the onset of this new regime of behaviour is suggestive of a common cause.

3. Recent Trends in the Rotational State: Methodology

[7] Trends in the polar wander signal have been examined through a recent set of independent space-geodetic Earth orientation measurements, which are generated annually by the Jet Propulsion Laboratory (JPL). The particular set used in this study, denoted SPACE2008, is available from JPL's Geodynamics and Space Geodesy Group via anonymous ftp at <ftp://euler.jpl.nasa.gov/keof/combinations/2008>, and spans the period from 28 September 1976 to 2 July 2009. It includes the values of the polar motion components at daily intervals, with components extending from the Conventional International Origin (CIO) along an x-axis aligned with the Greenwich meridian (Figure 1a), and along a y-axis aligned with the 90°W meridian (Figure 1c) [*Ratcliff and Gross*, 2010]. Linear trends in the polar motion series are studied by removing the large high-frequency variations that dominate the signal. In this study, a Butterworth-type low-pass filter is applied to the polar motion series [*Butterworth*, 1930], with a period cut-off set at 6 years, a value that is consistent with previous studies of polar motion trends [*Gross and Vondrák*, 1999]. The Butterworth filter is preferred to simpler, idealized digital filters such as the simple boxcar filter, as it has a maximally flat frequency response and phase shift effects that are simple to compensate. The smoothed series, shown in Figures 1a and 1c (for the x- and y-components, respectively), serve as the basis for the analysis of quasi-periodic low-frequency residual variability, using a methodology similar to that employed by *Gross and Vondrák* [1999]. Low-frequency and quasi-periodic terms are determined by performing a simultaneous weighted least-squares fit for a mean, a linear trend and low-frequency

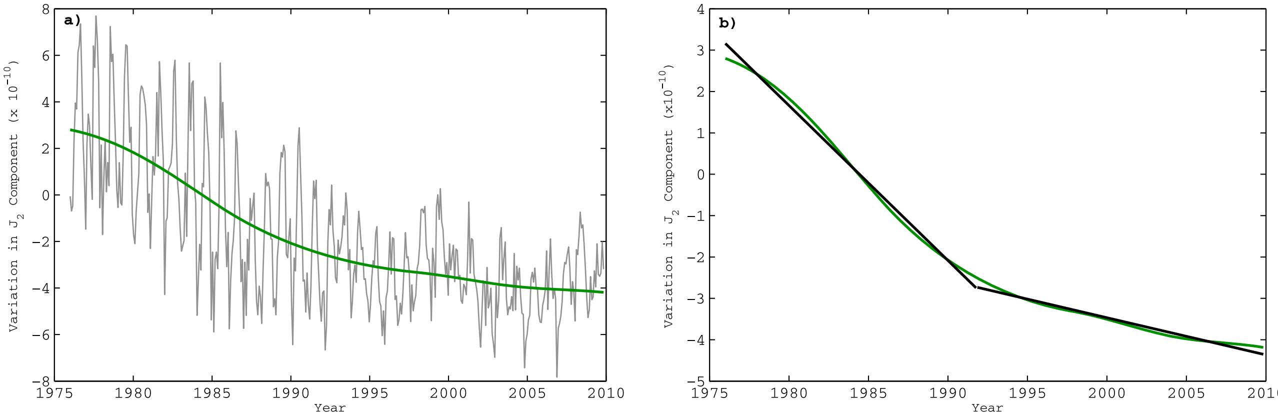

Figure 2. Changes in the J_2 Stokes coefficient ($\times 10^{-10}$), for the period 1976–2009, from the orbital parameters of seven geodetic satellites [*Cheng and Tapley*, 2004]. (a) Raw variations of J_2 ($\times 10^{-10}$) (dark grey), and subjected to a 20-year, low-pass filter (green). (b) Two linear fits for the time period 1976–1992 [rate: -0.37 (±0.01) $\times 10^{-10}$ yr^{-1}], and 1992–2009 [rate: -0.09 (±0.02) $\times 10^{-10}$ yr^{-1}].

periodic terms that correspond to the most prominent peaks in the amplitude spectrum of the time series. Changes in the linear trend for each component are then found by dividing the time series into two segments. The position of the "pivot-time" that separates the two segments is varied systematically, and the linear trend and mean are determined for each segment in order to find the pivot-time that minimizes the overall root-mean-square error of the fit. The quality of the best two segment fit is then compared to the best single segment fit. To be preferred, the best two segment fit must be characterized by a substantially lower root-mean-square error. The resulting two-segment fits to the low-pass filtered polar wander observations are presented in Figures 1b and 1d for the x- and y-components, respectively.

[8] Recent variations in the linear trends for the non-tidal acceleration of planetary rotation rate are analysed using the most recently available satellite laser ranging (SLR) data for a subset of seven geodetic satellites (Starlette, Ajisai, Stella, LAGEOS 1 and 2, Etalon-1 and -2, and BE-C (from 1999 on)) [*Cheng and Tapley*, 2004]. The available data, obtained via anonymous ftp from the Center for Space Research at the University of Texas at Austin, spans January 1976 to the end of 2009 and is presented in Figure 2a. In order to study variations in the linear trend over this period, low-frequency terms are also eliminated using a low-pass Butterworth filter. The cut-off for the analysis of this data is fixed at 20 years, which is sufficient to remove the suggested 18.6-year tidal and decadal variations, and is consistent with the analysis of *Cheng and Tapley* [2004]. The smoothed series, plotted in Figure 2a, reveals a marked change approximately in the mid-1990s. Linear trends are then determined in the smoothed J_2 series, by separating the time series into two parts and fitting the trend separately for each part, as for the polar motion. The pivot-time is again shifted along the series to find the position of the knot in time that minimizes the overall root-mean-square error of fit. The final result of this process is presented in Figure 2b.

4. Discussion and Conclusions

[9] Changes in the linear trends of the secular drift of the pole relative to the surface geography and of the non-tidal acceleration of the rate of rotation have been clearly identified. It is most revealing, however, to compare the variation of the total root-mean-square error for the two rotation-related time series as the position of the transition in the linear trend is varied systematically. These results are presented in Figure 3 and demonstrate that the transition in the linear trends for both anomalies occurs in approximately 1992.

[10] As shown in Table 1, this study of the polar motion time series demonstrates that its secular rate of drift remained approximately fixed, prior to 1992, at 4.5($\pm$0.1) mas/yr (1.3° Myr^{-1}), along the 68 ($\pm$8)°W meridian, while it slowed to 1.8 ($\pm$0.4) mas/yr (0.5° Myr^{-1}), along the 58 ($\pm$9)°W meridian subsequently. Although not corrected for plate tectonics in the hotspot frame of reference, as by *Argus and Gross* [2004], the current analysis demonstrates that dividing the time series into two distinct epochs increases the magnitude of the established secular rates of change prior to 1992, but decreases them for modern times subsequent to this. Concerning the corresponding changes in J_2, our analyses estimate a rate of change of -3.7 (±0.1) $\times 10^{-11}$ yr^{-1} before 1992, and -0.9 (±0.2) $\times 10^{-11}$ yr^{-1} after 1992. Splitting the time series fully reconciles the observed rate of change for J_2 presented by *Cheng and Tapley* [2004] with the estimate from historical records of *Stephenson and Morrison* [1995] [-3.5 (±0.8) $\times 10^{-11}$ yr^{-1}].

[11] The identification of significant shifts in the secular rates of change of the two primary Earth rotation observables, which become evident in the same epoch of time, is highly significant. This is especially the case as the variation in J_2 and polar wander are dependent upon completely independent elements of the Earth's moment of inertia tensor [e.g., *Munk and Macdonald*, 1960; *Peltier and Luthcke*, 2009]. In models of the GIA process, which are able to simultaneously fit these two rotational anomalies, variations in the elements of the moment of inertia tensor of the planet are determined by a specific model of time-dependent continental ice-sheet loading and of the depth-dependence of mantle viscosity. It would therefore be very surprising if the observed recent changes in the secular trends inferred to have occurred since 1992 were not caused by recent changes in surface ice sheet loading.

[12] Our hypothesis is that these simultaneous shifts in Earth's rotational state lie at the heart of the problem of the

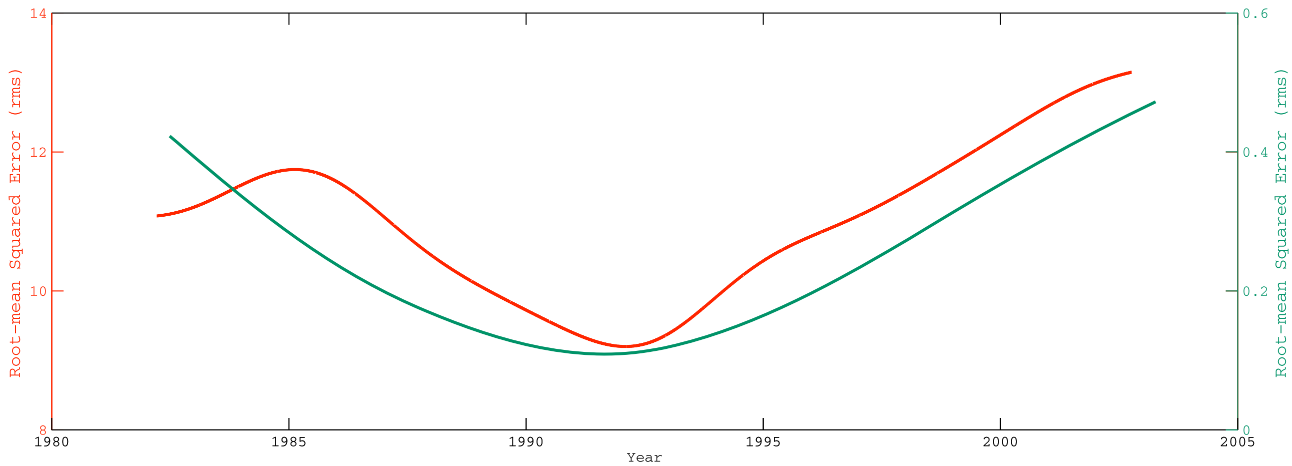

Figure 3. The total root-mean-squared error for the J_2 Stokes coefficient fit (dark green) and the polar wander fit (red), as a function of the position of the pivot-time, with a common minimum observed around 1992.

misfit between GRACE observations of the time derivatives of the degree two and order one Stokes coefficients and the values predicted by the ICE-5G (VM2) model of the GIA process, as recently discussed by *Peltier and Luthcke* [2009]. In their analysis, the authors suggested that the misfit could be due to the fact that the ICE-5G (VM2) model of the GIA process is designed to fit only data that is unambiguously associated with the Late Quaternary ice-age. The model specifically does not include the influence of the additional changes in continental ice-cover associated with the modern global warming process. Further analysis of this misfit by *Peltier and Drummond* [2010] has demonstrated that it could not be eliminated by reasonable variations of the model of the radial variation of mantle viscosity. This conclusion reinforces the plausibility of the hypothesis by *Peltier and Luthcke* [2009] as does the present analysis demonstrating that polar wander has shifted into a new state during the GRACE era.

[13] The existence of a link between the timing of the changes in the linear trends for the rotational state anomalies and recent changes in the ice sheet loading on the planet is supported by studies of the year-to-year melting rates of major continental ice sheets and of small ice sheets and glaciers distributed globally. For instance, *Thomas et al.* [2006] compared various estimates of the time dependence of elevation changes and mass balance for the Greenland Ice Sheet, and suggested that satellite altimetry measurements might seriously underestimate Greenland ice losses, and that all other indicators, such as snow-accumulation rates and airborne laser altimetry measurements, support the idea of a sharp decrease in ice sheet mass beginning in the mid-1990s. Another study, by *Jiang et al.* [2010], based solely on the inferred acceleration of uplift rates in the North Atlantic region, is interpreted to imply accelerated melting of coastal continental ice since the mid-1990s.

[14] The validation of the Peltier and Lutchke hypothesis concerning the origins of the inferred misfit between the ICE-5G (VM2) prediction of the time derivatives of the degree two and order one Stokes coefficients and the GRACE inferences of the same properties of Earth's gravitational field will require the development of a forward model that is in accord with the known characteristics of modern continental ice-sheet disintegration and global sea-level observations. This will require the augmentation of the ICE-5G (VM2) structure to include this additional source of rotational forcing. We will report the required detailed analyses of this kind

Table 1. Inter-study Comparison of Secular Trends in Polar Wander and J_2

Source	Fits	Time Covered	Polar Motion (mas yr^{-1})	Direction
		Polar Wander		
Argus and Gross [2004] (ILS) (relative to mean lithosphere)	1	1899–1979	3.53	79.9°W
Gross and Vondrák [1999] (HIPPARCOS)	1	1900–1992	3.51	79.2°W
Gross and Vondrák [1999] (SPACE96)[a]	1	1976–1997	4.12	73.9°W
Gross and Poutanen [2009] (SPACE2007)[a]	2	1976–1995	4.23	72.2°W
		1995–2007	2.92	64.8°W
This Study (SPACE2008)	2	1976–1992	4.5(±0.1)	68(±8)°W
		1992–2008	1.8(±0.4)	58(±9)°W
Source	**Fits**	**Time Covered**	J_2 ($\times 10^{-11}$ yr^{-1})	
		J_2		
Yoder et al. [1983]	1	1978–1983	−3.5	
Stephenson and Morisson [1995]	1	700BC–1600AD	−3.5 (±0.8)	
Cheng and Tapley [2004]	1	1976–2004	−2.75	
This Study	2	1976–1992	−3.7 (±0.1)	
		1992–2009	−0.9 (±0.2)	

[a]SPACE2007 and SPACE96 are two earlier versions of the SPACE2008 Earth Orientation Parameters-based data series for polar motion.

elsewhere. In the absence of the demonstration herein of the occurrence of a marked change in rotational state prior to the launch of the GRACE satellite, work of this kind would not be warranted.

[15] **Acknowledgments.** We are indebted to our colleagues Minkang Cheng from the Center for Space Research of the University of Texas at Austin, and Richard S. Gross from the Jet Propulsion Laboratory of the California Institute of Technology for allowing us to access the latest time series for J_2 and for Earth Orientation Parameters, respectively. One of us (W.R.P.), while attending the June 2009 meeting on glacial isostatic adjustment that was held in Espoo, Finland, and summarized by *Gross and Poutanen* [2009], pointed out the fact that these two time series apparently began to depart from their long established GIA-related trends at the same time. In the present paper, the striking nature of the simultaneity of this departure is established on quantitative grounds.

[16] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Argus, D. F., and R. S. Gross (2004), An estimate of motion between the spin axis and the hotspots over the past century, *Geophys. Res. Lett.*, *31*, L06614, doi:10.1029/2004GL019657.

Butterworth, S. (1930), On the theory of filter amplifiers, *Wireless Eng.*, *7*, 536–541.

Cheng, M., and B. D. Tapley (2004), Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, *109*, B09402, doi:10.1029/2004JB003028.

Clark, J. A., W. E. Farrell, and W. R. Peltier (1978), Global changes in postglacial sea levels: A numerical calculation, *Quat. Res.*, *9*, 265–287, doi:10.1016/0033-5894(78)90033-9.

Cox, C. M., and B. F. Chao (2002), Detection of a large-scale mass redistribution in the terrestrial system since 1998, *Science*, *297*(5582), 831–833, doi:10.1126/science.1072188.

Dickey, J. O., S. L. Marcus, O. de Viron, and I. Fukumori (2002), Recent Earth oblateness variations: Unravelling climate and postglacial rebound effects, *Science*, *298*(5600), 1975–1977, doi:10.1126/science.1077777.

Farrell, W. E., and J. A. Clark (1976), On postglacial sea level, *Geophys. J. R. Astron. Soc.*, *46*(3), 647–667, doi:10.1111/j.1365-246X.1976.tb01252.x.

Gross, R. S. (2000), The excitation of the Chandler wobble, *Geophys. Res. Lett.*, *27*(15), 2329–2332, doi:10.1029/2000GL011450.

Gross, R. S., and M. Poutanen (2009), Geodectic observations of glacial isostatic adjustment, *Eos Trans. AGU*, *90*(41), doi:10.1029/2009EO410004.

Gross, R. S., and J. Vondrák (1999), Astrometric and space-geodetic observations of polar wander, *Geophys. Res. Lett.*, *26*(14), 2085–2088, doi:10.1029/1999GL900422.

Hide, R., N. T. Birch, L. V. Morrison, D. J. Shea, and A. A. White (1980), Atmospheric angular momentum fluctuations and changes in the length of the day, *Nature*, *286*(5769), 114–117, doi:10.1038/286114a0.

Jiang, Y., T. H. Dixon, and S. Wdowinski (2010), Accelerating uplift in the North Atlantic region as an indicator of ice loss, *Nat. Geosci.*, *3*, 404–407, doi:10.1038/ngeo845.

Munk, W. H., and G. J. F. Macdonald (1960), *The Rotation of the Earth: A Geophysical Discussion*, Cambridge Univ. Press, Cambridge, U. K.

Peltier, W. R. (1974), The impulse response a Maxwell Earth, *Rev. Geophys.*, *12*(4), 649–669, doi:10.1029/RG012i004p00649.

Peltier, W. R. (1976), Glacial isostatic adjustment II: The inverse problem, *Geophys. J. R. Astron. Soc.*, *46*(3), 669–705, doi:10.1111/j.1365-246X.1976.tb01253.x.

Peltier, W. R. (1982), Dynamics of the ice-age Earth, *Adv. Geophys.*, *24*, 1–146, doi:10.1016/S0065-2687(08)60519-1.

Peltier, W. R. (1983), Constraint on deep mantle viscosity from Lageos acceleration data, *Nature*, *304*, 434–436, doi:10.1038/304434a0.

Peltier, W. R. (2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci.*, *32*, 111–149, doi:10.1146/annurev.earth.32.082503.144359.

Peltier, W. R. (2007), History of Earth rotation, in *Treatise on Geophysics*, vol. 9, *Evolution of the Earth*, edited by G. Schubert, pp. 243–293, Elsevier, Oxford, U. K., doi:10.1016/B978-044452748-6.00148-6.

Peltier, W. R., and J. T. Andrews (1976), Glacial isostatic adjustment I: The forward problem, *Geophys. J. R. Astron. Soc.*, *46*(3), 605–646, doi:10.1111/j.1365-246X.1976.tb01251.x.

Peltier, W. R., and R. Drummond (2010), Deepest mantle viscosity: Constraints from Earth rotation anomalies, *Geophys. Res. Lett.*, *37*, L12304, doi:10.1029/2010GL043219.

Peltier, W. R., and S. B. Luthcke (2009), On the origins of Earth rotation anomalies: New insights on the basis of both "paleogeodetic" data and Gravity Recovery and Climate Experiment (GRACE) data, *J. Geophys. Res.*, *114*, B11405, doi:10.1029/2009JB006352.

Peltier, W. R., W. E. Farrell, and J. A. Clark (1978), Glacial isostasy and relative sea-level: A global finite element model, *Tectonophysics*, *50*, 81–110, doi:10.1016/0040-1951(78)90129-4.

Ratcliff, J. T., and R. S. Gross (2010), Combinations of Earth orientation measurements: SPACE2008, COMB2008, and POLE2008, *JPL Publ.*, 10-4.

Stephenson, E. R., and L. V. Morrison (1995), Long term fluctuations in the Earth's rotation: 700 B.C. to A.D. 1990, *Philos. Trans. R. Soc. London, Ser. A*, *351*, 165–202, doi:10.1098/rsta.1995.0028.

Thomas, R., E. Frederick, W. Krabill, S. Manizade, and C. Martin (2006), Progressive increase in ice loss from Greenland, *Geophys. Res. Lett.*, *33*, L10503, doi:10.1029/2006GL026075.

Wu, P., and W. R. Peltier (1984), Pleistocene deglaciation and the Earth's rotation: A new analysis, *Geophys. J. R. Astron. Soc.*, *76*(3), 753–791, doi:10.1111/j.1365-246X.1984.tb01920.x.

Yoder, C. F., J. G. Williams, J. O. Dickey, B. E. Schutz, R. J. Eanes, and B. D. Tapley (1983), Secular variation of the Earth's gravitational harmonic J_2 coefficient from LAGEOS and non-tidal acceleration of Earth rotation, *Nature*, *303*, 757–762, doi:10.1038/303757a0.

Yumi, S., and K. Yokoyama (1980), *Results of the International Latitude Service in a homogeneous system, 1899.9-1979.0*, Cent. Bur. of the Int. Polar Motion Serv., Mizusawa, Japan.

W. R. Peltier and K. Roy, Department of Physics, University of Toronto, 60 St. George St., Toronto, ON M5S 1A7, Canada. (peltier@atmosp.physics.utoronto.ca; kroy@atmosp.physics.utoronto.ca)