

Mass Transport and Dynamics in the Earth System: The Unsolved Scientific Questions and Observational Requirements

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Abstract

The Earth is a dynamic system—it has a fluid, mobile atmosphere and oceans, a continually changing global distribution of ice, snow, and water, a fluid core that is undergoing some type of hydromagnetic motion, a mantle both thermally convecting and rebounding from the glacial loading of the last ice age, and mobile tectonic plates. In addition, external forces due to the gravitational attraction of the Sun, Moon, and planets also act upon the Earth. These internal dynamical processes and external gravitational forces exert torques on the solid Earth, or displace its mass, thereby causing the Earth's rotation, gravitational field, and shape to change. Geodetic observing systems, both space-based and ground-based, provide the measurements of the Earth's rotation, gravitational field, and shape that are used to study the response of the Earth to these dynamical forces, thereby allowing inferences to be made about the internal structure of the Earth. In this position paper, some scientific questions regarding the structure of the Earth that can be addressed by geodetic measurements will be discussed along with the requirements on the geodetic observing systems that will be needed in order to answer these questions.

Introduction

The solid Earth is subject to a wide variety of forces including external forces due to the gravitational attraction of the Sun, Moon, and planets, surficial forces due to the action of the atmosphere, oceans, and water stored on land, and internal forces due to earthquakes and tectonic motions, mantle convection, and coupling between the mantle and both the fluid outer core and the solid inner core. The solid Earth responds to these forces by displacing its mass, deforming its shape, and changing its rotation. Geodetic observing systems can measure the change in the Earth's gravity caused by mass displacement, the change in the Earth's shape, and the change in the Earth's rotation. Consequently, geodetic observing systems can be used to study both the mechanisms causing the Earth's shape, rotation, and gravity to change, as well as the response of the solid Earth to these forcing mechanisms. As a result, geodetic observing systems can be used to gain greater understanding of the Earth's interior structure and of the nature of the forcing mechanisms including their temporal evolution. A few selected unsolved scientific questions will be examined here as a way of illustrating the role that geodetic observing systems play in understanding the Earth and its interacting systems.

Climate Change, Ice Mass Balance, and Sea Level Change

Climate models that are used to study the effects of atmospheric greenhouse gases predict an overall increase in the global temperature over the next century of from 1.4 to 5.8 degrees centigrade (Houghton *et al.*, 1996, 2001). An increase of this magnitude could have numerous catastrophic effects, not the least of which might be a global rise in sea level due to a combination of melting polar ice sheets and glaciers and the thermal expansion of sea water. The

global rate of sea level rise during the last century has apparently been somewhat in excess of 1 mm/yr (Douglas *et al.*, 2001). One of the important goals of all national and international global change programs is to improve our understanding of the mechanisms and implications of observed sea level changes.

Altimetry measurements by TOPEX/Poseidon and its follow-on, Jason-1, allow the determination of the sea surface height which varies due to both thermal expansion of sea water and changes in ocean water mass arising from changes in polar ice cap, mountain glacier mass, and groundwater storage. Since gravitational field observations, such as those from GRACE, are sensitive to processes that change the Earth's mass distribution, they can be used to investigate sea level rise / ice sheet mass changes. Moreover, since the Earth's gravitational field is not sensitive to thermal expansion of sea water, observations of the gravitational field can be used in concert with sea level change observations to separate the change due to thermal expansion / contraction from that due to oceanic mass changes, thereby helping to quantify the extent to which greenhouse warming is sequestered in the oceans (cf. Watts and Morantine, 1991).

The rotation vector of the solid Earth exhibits minute but complicated changes of up to several parts in 10^8 in speed [corresponding to a variation of several milliseconds (ms) in the length of the day $\Lambda(t)$], and about one part in 10^6 in the orientation of the rotation axis relative to the solid Earth's axis of figure [corresponding to a variation of several hundred milliarcseconds (mas) in polar motion]. The principle of conservation of angular momentum requires that changes in the rotation vector of the solid Earth must be manifestations of (a) torques acting on the solid Earth or (b) changes in the mass distribution within the solid Earth, which alter its inertia tensor. Angular momentum transfers occur between the solid Earth and the fluid regions (the underlying liquid metallic core and the overlying hydrosphere and atmosphere) with which it is in contact; concomitant torques are due to hydrodynamic or magnetohydrodynamic stresses acting at the fluid / solid Earth interfaces. Thus, as the angular momentum of the hydrosphere changes because of sea level rise / ice sheet mass variations, the angular momentum of the solid Earth will change thereby giving rise to changes in the solid Earth's rotation vector.

Geodetic gravitational field and Earth rotation observations can thus be used in concert with TOPEX/Poseidon and Jason-1 sea surface height measurements to investigate sea level change, an important consequence and metric of global warming. At a more fundamental level, geodetic observations are used to precisely determine the orbit of the satellite altimeters that are used to make the sea surface height measurements. Geodetic observations are also used to determine the terrestrial reference frame within which the sea level is measured. Since the global rate of sea level rise is on the order of 1 mm/yr, the underlying reference frame should be accurate and stable to at least an order of magnitude better than this, or to within 0.1 mm/yr. This implies that site positions, including the vertical, need to be determined with sub-millimeter accuracy.

Chandler Wobble Excitation, Eigenfrequency, and Mantle Anelasticity

Any irregularly shaped solid body rotating about some axis that is not aligned with its figure axis will freely wobble as it rotates. For the Earth, this Eulerian free wobble is known as the Chandler wobble in honor of Seth Carlo Chandler, Jr. who first observed it in 1891 (Chandler, 1891). Frictional forces associated with the wobble-induced deformation of the solid Earth would cause the Chandler wobble to freely decay with an exponential time constant of about 68 years if no mechanism or mechanisms were acting to excite it. Observations of the

Chandler wobble taken during the past century show that there are times when the amplitude of the Chandler wobble has actually increased. Thus, some mechanism or mechanisms must clearly be acting to excite the Chandler wobble. While there is growing agreement that the Chandler wobble is excited by a combination of atmospheric, oceanic, and hydrologic processes, the relative contribution of each process to its excitation is still being debated. For example, Gross *et al.* (2003) studied the excitation of the Chandler wobble during 1980–2000, finding that atmospheric winds and surface pressure and oceanic currents and bottom pressure combined are significantly coherent with and have enough power to excite the Chandler wobble. They found that during this time interval the observed power in the Chandler band is 1.90 mas^2 , with the sum of all atmospheric and oceanic excitation processes having more than enough power, at 2.22 mas^2 , to excite the Chandler wobble. Ocean-bottom pressure variations were found to be the single most effective process exciting the Chandler wobble, with atmospheric surface pressure variations having about $2/3$ as much power as ocean-bottom pressure variations, and with the power of winds and currents combined being less than $1/3$ the power of the combined effects of surface and bottom pressure. The conclusion that oceanic processes are more effective than atmospheric in exciting the Chandler wobble has also been reached by Gross (2000), Brzezinski and Nastula (2002), Brzezinski *et al.* (2002), and Liao *et al.* (2003).

Studies of the excitation of the Chandler wobble using coupled atmosphere-ocean climate models also confirm that atmospheric and oceanic processes have enough power to maintain the Chandler wobble and indicate that the relative contribution of individual atmospheric and oceanic processes changes with time (Celaya *et al.*, 1999; Leuliette and Wahr, 2002; Ponte *et al.*, 2002). However, other studies have concluded that atmospheric processes alone have enough power to excite the Chandler wobble (Furuya *et al.*, 1996, 1997; Aoyama and Naito, 2001; Aoyama *et al.*, 2003; Aoyama, 2005). Resolution of the debate about the relative importance of atmospheric, oceanic, and hydrologic processes to exciting the Chandler wobble awaits the availability of more accurate measurements and models of these processes and, because the power needed to maintain the Chandler wobble depends upon its damping (Gross, 2000), of more accurate estimates of its period and Q .

Determining an unbiased estimate for the period and Q of the Chandler wobble is complicated by the relatively short duration of the observational record and by incomplete and inaccurate models of the mechanisms acting to excite it. In the absence of any knowledge of its excitation, statistical models of the excitation can be adopted (e.g., Jeffreys, 1972; Wilson and Haubrich, 1976; Ooe, 1978; Wilson and Vicente, 1980, 1990). Since atmospheric, oceanic, and hydrologic processes are thought to be major sources of Chandler excitation, its period and Q have also been estimated by using atmospheric angular momentum (AAM) data (Furuya and Chao, 1996; Kuehne *et al.*, 1996), atmospheric and oceanic angular momentum (OAM) data (Gross, 2005), and atmospheric, oceanic, and hydrologic angular momentum data (Wilson and Chen, 2005). Table 1 gives the resulting estimates for the period and Q of the Chandler wobble. As can be seen, the range in the estimates of the period is greater than the uncertainty in their determination. Also, there is a disparity between the estimates of the Q determined using statistical models of the excitation mechanism and those using AAM and OAM data or those using just AAM data. The most recent estimate for the Q using a statistical model of the excitation, that of Wilson and Vicente (1990), yields a value for the Q of 179, whereas the value determined by Gross (2005) is 62.3, which is outside the quoted uncertainty of the Wilson and Vicente (1990) estimate. This disparity between the Q values obtained using a statistical model for the excitation, and those using OAM and/or AAM data is disturbing since it raises the

Table 1 Estimated period and Q of Chandler wobble.

<i>Period</i> (solar days)	<i>Q</i>	<i>Data Span</i> (years)	<i>Source</i>
<i>Statistical excitation</i>			
433.2 ± 2.2	63 (36, 192)	67.6	(a)
434.0 ± 2.6	100 (50, 400)	70	(b)
434.8 ± 2.0	96 (50, 300)	76	(c)
433.3 ± 3.1	170 (47, 1000)	78	(d)
433.0 ± 1.1	179 (74, 789)	86	(e)
433.1 ± 1.7	—	93	(f)
<i>Atmospheric excitation</i>			
439.5 ± 2.1	72 (30, 500)	8.6	(g)
433.7 ± 1.8	49 (35, 100)	10.8	(h)
<i>Atmospheric and oceanic excitation</i>			
431.7	62.3	21	(i)

The 1σ confidence interval for the Q estimates is given in parentheses. Sources: (a) Jeffreys (1972); (b) Wilson and Haubrich (1976); (c) Ooe (1978); (d) Wilson and Vicente (1980); (e) Wilson and Vicente (1990); (f) Vicente and Wilson (1997); (g) Kuehne *et al.* (1996); (h) Furuya and Chao (1996); (i) Gross (2005).

question of possible biases in the estimated values (Wilson and Vicente, 1990; Furuya and Chao, 1996; Kuehne *et al.*, 1996; Vicente and Wilson, 1997). The biases may be inherent in the method used to determine the values, or they may be due to the relative shortness of the series. It is curious that the estimates based upon the shorter space-geodetic polar motion series (21, 10.8, or 8.6 years) all yield lower values for the Q of the Chandler wobble than do the most recent estimates based upon the longer ILS polar motion series (86, 78 years). Gross (2005) discusses the sensitivity of the estimated period and Q of the Chandler wobble to the length of the data sets that he analyzed, concluding that data sets spanning at least 31 years are needed to obtain stable estimates. He also notes the need for Monte Carlo simulations to determine corrections to the bias of the estimated Q values.

Unlike the forced wobbles of the Earth, such as the annual wobble, whose periods are the same as the periods of the forcing mechanisms, the period of the free Chandler wobble is a function of the internal structure and rheology of the Earth, and its decay time constant, or quality factor Q , is a function of the dissipation mechanisms acting to dampen the free wobble. Better, more accurate, determinations of the period and Q of the Chandler wobble can thus be used to better understand the internal structure of the Earth and the dissipation mechanism(s) that are acting to dampen the Chandler wobble. Mantle anelasticity is one possible dissipation mechanism of the Chandler wobble and is also responsible for the decay of both seismic waves and the Earth's normal modes. Assuming that a single absorption band extends from the Chandler frequency to seismic frequencies, then the observed values for the period and quality factor Q of the Chandler wobble can be used to estimate the frequency dependence of the dissipation. Placing useful constraints on this frequency dependence will require reducing the uncertainty in the estimates of the period and Q of the Chandler wobble by at least a factor of five.

Discussion

As illustrated by these two examples, improved geodetic measurements will be required to gain greater understanding of the dynamic Earth and its interacting systems. Reference frame accuracy and stability must be improved by at least an order of magnitude in order to provide the required framework for the collection and analysis of space-based and ground-based observations. Earth orientation parameters, which link the terrestrial and celestial reference frames, must have similar accuracy and stability as the reference frames in order to be consistent with them. Improving the accuracy of the Earth orientation parameters will allow additional resonances, besides the Chandler wobble and Free Core Nutation, to be observed thereby gaining greater understanding of the interior structure of the Earth. Analysis of GRACE observations has proved the utility of space-based gravity measurements to gain greater understanding of mass transport in the Earth system. But the current limitations on accuracy and resolution, both spatial and temporal, of these measurements are frustrating. At least an order of magnitude increase in spatial resolution and two orders of magnitude increase in accuracy are needed.

But improved measurements are not enough. The geodetic observing systems must be made consistent with each other. Models of the geophysical fluids that are used in reducing geodetic observations must be improved if the accuracy of the observations are to be improved. Models of the Earth's interior structure, such as the anelasticity of the mantle, must also be improved in order to improve the accuracy of the products of the geodetic observing systems. And the underlying theory used to interpret the geodetic observations must be improved as the accuracy of the measurements are improved. For example, the usual equations used to interpret Earth orientation observations are linearized, with terms of order higher than about 1 part in 300 being discarded. But Earth orientation measurements are currently accurate to about 1 part in 1000. So, in Earth rotation studies, the measurements are currently more accurate than the theory being used to interpret them.

Finally, while it is straightforward to lay out the necessary pathways to improve the accuracy, stability, and consistency of geodetic observing systems, following these pathways will require dedication and commitment on the part of both the geodetic community and of the funding agencies.

References

- Aoyama, Y., Quasi-14 month wind fluctuation and excitation of the Chandler wobble, in *Forcing of Polar Motion in the Chandler Frequency Band: A Contribution to Understanding Interannual Climate Change*, edited by. H.-P. Plag, B. F. Chao, R. S. Gross, and T. van Dam, pp. 135-141, Cahiers du Centre Européen de Géodynamique et de Séismologie vol. 24, Luxembourg, 2005.
- Aoyama, Y., and I. Naito, Atmospheric excitation of the Chandler wobble, 1983–1998, *J. Geophys. Res.*, 106(B5), 8941-8954, 2001.
- Aoyama, Y., I. Naito, T. Iwabuchi, and N. Yamazaki, Atmospheric quasi-14 month fluctuation and excitation of the Chandler wobble, *Earth Planets Space*, 55, e25-e28, 2003.

- Brzezinski, A., and J. Nastula, Oceanic excitation of the Chandler wobble, *Adv. Space Res.*, *30*, 195-200, 2002.
- Brzezinski, A., J. Nastula, and R. M. Ponte, Oceanic excitation of the Chandler wobble using a 50-year time series of ocean angular momentum, in *Vistas for Geodesy in the New Millennium*, edited by J. Adám and K.-P. Schwarz, pp. 434-439, IAG Symposia vol. 125, Springer-Verlag, New York, 2002.
- Celaya, M. A., J. M. Wahr, and F. O. Bryan, Climate-driven polar motion, *J. Geophys. Res.*, *104*, 12813-12829, 1999.
- Chandler, S. C., On the variation of latitude, I, *Astron. J.*, *11*, 59-61, 1891.
- Douglas, B. C., M. S. Kearney, and S. P. Leatherman (Eds.), *Sea level rise: History and Consequences*, 242 pp., Academic Press, San Diego, Calif., 2001.
- Furuya, M., and B. F. Chao, Estimation of period and Q of the Chandler wobble, *Geophys. J. Int.*, *127*, 693-702, 1996.
- Furuya, M., Y. Hamano, and I. Naito, Quasi-periodic wind signal as a possible excitation of Chandler wobble, *J. Geophys. Res.*, *101*, 25537-25546, 1996.
- Furuya, M., Y. Hamano, and I. Naito, Importance of wind for the excitation of Chandler wobble as inferred from wobble domain analysis, *J. Phys. Earth*, *45*, 177-188, 1997.
- Gross, R. S., The excitation of the Chandler wobble, *Geophys. Res. Lett.*, *27*, 2329-2332, 2000.
- Gross, R. S., The observed period and Q of the Chandler wobble, in *Forcing of Polar Motion in the Chandler Frequency Band: A Contribution to Understanding Interannual Climate Change*, edited by H.-P. Plag, B. F. Chao, R. S. Gross, and T. van Dam, pp. 31-37, Cahiers du Centre Européen de Géodynamique et de Séismologie vol. 24, Luxembourg, 2005.
- Gross, R. S., I. Fukumori, and D. Menemenlis, Atmospheric and oceanic excitation of the Earth's wobbles during 1980–2000, *J. Geophys. Res.*, *108*(B8), 2370, doi:10.1029/2002JB002143, 2003.
- Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (Eds.), *Climate Change 1995: The Science of Climate Change*, 584 pp., Cambridge University Press, New York, 1996.
- Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.), *Climate Change 2001: The Scientific Basis*, 584 pp., Cambridge University Press, New York, 2001.
- Jeffreys, H., The variation of latitude, in *Rotation of the Earth*, edited by P. Melchior and S. Yumi, pp. 39-42, Int. Astron. Union Symp. No. 48, D. Reidel, Dordrecht, Holland, 1972.

- Kuehne, J., C. R. Wilson, and S. Johnson, Estimates of the Chandler wobble frequency and Q , *J. Geophys. Res.*, *101*, 13573-13579, 1996.
- Liao, D., X. Liao, and Y. Zhou, Oceanic and atmospheric excitation of the Chandler wobble, *Geophys. J. Int.*, *152*, 215-227, 2003.
- Leuliette, E. W., and J. M. Wahr, Climate excitation of polar motion., in *Vistas for Geodesy in the New Millennium*, edited by J. Adám and K.-P. Schwarz, pp. 428-433, IAG Symposia vol. 125, Springer-Verlag, New York, 2002.
- Ooe, M., An optimal complex ARMA model of the Chandler wobble, *Geophys. J. Roy. astr. Soc.*, *53*, 445-457, 1978.
- Ponte, R. M., J. Rajamony, and J. M. Gregory, Ocean angular momentum signals in a climate model and implications for Earth rotation, *Clim. Dyn.*, *19*, 181-190, 2002.
- Vicente, R. O., and C. R. Wilson, C. R., On the variability of the Chandler frequency, *J. Geophys. Res.*, *102*, 20439-20445, 1997.
- Watts, R. C., and M. C. Morantine, Is the greenhouse gas-climate signal hiding in the deep ocean?, *Climatic Change*, *18*, iii-vi, 1991.
- Wilson, C. R., and J. Chen, Estimating the period and Q of the Chandler wobble, in *Forcing of Polar Motion in the Chandler Frequency Band: A Contribution to Understanding Interannual Climate Change*, edited by H.-P. Plag, B. F. Chao, R. S. Gross, and T. van Dam, pp. 23-29, Cahiers du Centre Européen de Géodynamique et de Séismologie vol. 24, Luxembourg, 2005.
- Wilson, C. R., and R. A. Haubrich, Meteorological excitation of the Earth's wobble, *Geophys. J. Roy. astr. Soc.*, *46*, 707-743, 1976.
- Wilson, C. R., and R. O. Vicente, An analysis of the homogeneous ILS polar motion series, *Geophys. J. Roy. astr. Soc.*, *62*, 605-616, 1980.
- Wilson, C. R., and R. O. Vicente, Maximum likelihood estimates of polar motion parameters, in *Variations in Earth Rotation*, edited by D. D. McCarthy and W. E. Carter, pp. 151-155, American Geophysical Union Geophysical Monograph Series, Washington, DC, 1990.