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Studies of Water Storage and Other Contributions to Changes in the Rotation of the Earth.

Clark R. Wilson, Principal Investigator
University of Texas at Austin
Center for Space Research, Institute for Geophysics
Department of Geological Sciences

Summary: The principal focus of this study has been to determine the effects of the global redistribution of water mass on various geodetic observables, especially polar motion, and complementary observables such as geodetic satellite positions. The effect of water mass redistribution has been and continues to be less well known and more difficult to observe than effects of air mass redistribution, yet the water contribution is potentially significant over a large range of periods. This report reviews the current understanding of the contribution to polar drift, decadal polar motion, Chandler and annual wobbles, and higher frequency polar motion, as determined through the efforts of the funded work within the NASA Crustal Dynamics Project, and in the context of the general literature on the subject. Water mass redistribution is either demonstrably important to the excitation of each of these, or is probably important given a lack of other likely excitation sources. The list of publications supported by this grant documents full involvement of the Principal Investigator and co-workers in the activities of the Crustal Dynamics Project, and the development of space geodetic methods.

1. Introduction

It has been recognized since the study of Jeffreys (1916) that the variable load of water on the earth's surface may make a significant contribution to the excitation of polar motion. Given that a centimeter of water is equivalent in load to a millibar of air pressure, it is clear that water mass effects might easily be comparable to the well-documented air load contributions associated with fluctuations of a few millibars. Yet, there are comparatively few studies in the literature that are concerned with the water contribution. The lack of focus on the contribution of water mass is without doubt due to the difficulty of obtaining adequate data to estimate the effect. Water is stored and exchanged among many reservoirs on land, including vegetation, ground water, lakes, ice, and snow; many of these reservoirs of water mass are poorly observed; there is incomplete understanding of the water budget on land, even for limited well-studied regions; the polar motion problem demands global measures; most water is resident in the oceans and has been inaccessible to observation; ice sheet water budgets are poorly known; and global meteorological models and data used in weather forecasting do not properly treat the water cycle. The main motivation for further study of the water contribution is that it has not been possible to account for observed polar motion over a broad range of periods, ranging from weeks to decades. Yet, it is clear that air or water in some combination are probably responsible for much of the motion. This is certainly true at the annual period, but is likely true over the entire spectrum yet observed. Other sources of polar motion excitation, such as the core or earthquakes, are possible broad-band excitation sources, but their contributions have not yet been shown to be significant compared to air and water.

2. Water contributions to polar motion excitation

In this section, the contribution of water is reviewed for a range of polar motion time scales. For time scales of a year and longer, the most useful polar motion data set is the ILS series (Yumi and Yokoyama, 1980) containing monthly mean pole positions reported since January 1900. For shorter time scales, the space geodetic data from VLBI and SLR techniques is useful.The ILS time series is conveniently considered to be the sum of three components representing distinct time scales of motion. These terms are: A linear trend fit to the separate X and Y components; Decade-scale fluctuations about this linear drift, at periods longer than about two years; and Annual and Chandler frequency wobbles. At frequencies above 1 cycle per year, the ILS data are probably dominated by noise, and the space-geodetic data become useful.

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A. Drift

The average position of the rotation axis, calculated on an annual basis, has moved significantly since the turn of the century, which marked the beginning of the ILS observational program. The drift is most obvious in the Y-coordinate when examining the time series, but estimates indicate about 1.4 mas (milli-arc seconds) per year in X and 3.1 mas per year in the Y direction (Wilson and Vicente, 1980). The velocity vector thus is in a direction of about 66 degrees West Longitude with a magnitude of about 3.4 mas per year. The more recent space geodetic observations show a similar direction of drift. (IERS Annual Report,1990 page I-21). Estimates of the direction and magnitude of this drift will vary depending upon the duration of the time series, whether annual and Chandler terms are removed, and the details of the least squares fit. Wu and Peltier (1984) have demonstrated the general agreement between the observed drift of the pole and the drift expected from the effects of postglacial rebound. The details of the predicted postglacial rebound effects will vary depending upon the adopted ice sheet melting model, and other parameters, but the general conclusion seems firm. The drift of the pole in this century is dominantly the delayed response of the earth to continental water storage changes that took place over 10,000 years ago with the melting of the last great continental ice sheets. Thus, water mass redistribution is the likely cause of polar motion at the longest time scale contained in the ILS data.

B. Decade Scale Variability

Superimposed on the linear drift, but at periods longer than about 2 years, there is irregular polar motion. Fluctuations in this frequency range have been controversial. There have been suggestions that the motion is an artifact of poor or inadequate data. Gross (1990) analyzed the individual ILS station data to show that these fluctuations are probably real polar motion, however. Polar motion near a period of 30 years has also been proposed to be a free mode of the earth often termed the "Markowitz Wobble" (Dickman, 1980, but see also Vicente and Wilson,1980 and Wahr, 1984). A simpler hypothesis, from a physical standpoint, is that polar motion at decadal periods is forced by agents on or within the earth. The core has often been invoked as a forcing agent (Hinderer et al, 1987) but its inaccessibility makes it difficult to test this hypothesis. The remaining possibility is that the forcing is at surface of the earth, by air or water. Although both relative motion (winds and currents) and mass load (barometric pressure or water load) may contribute, water loads seems to be the most likely to be active at decadal time scales. This is because water can accumulate in various forms and remain for many years, while air mass cannot accumulate in the same way. Support for the importance of water storage at longer periods comes from the study of Kuehne and Wilson (1991) who show that the air mass excitation spectrum is roughly flat, or white, while the water spectrum is probably red, similar to the observed spectral shape of the ILS data.

The hypothesis that water mass redistribution is forcing the decade scale polar motion is strengthened by recognizing that much of this motion is linearly polarized, This linear polarization has been noted in the past, but it has not been widely recognized that the longitude is approximately that which would result from a simple sealevel rise or fall. This longitude is nearly orthogonal to that associated with polar drift, implying a separate forcing mechanism, and justifying the separation of the two components. To illustrate the linear polarization of long period motion, and its relationship to the oceans, the complex polar motion series can be decomposed into two parts. One is the projection along 52 degrees east-128 degrees west longitude which would be produced by a simple sea level change (Chao and O'Connor, 1988a), and the other is the component along the orthogonal direction. Fourier power spectra of the two time series show that below 0.1 cpy, the component that would be produced by a simple sealevel change is 10db above the orthogonal component. Thus virtually all polar motion at frequencies below 0.1 cpy is confined to the component along (52 E-128 W). This strongly suggests that polar motion at periods longer than a decade, but distinct from the drift over thousands of years, is forced by mass redistribution having the same geographical distribution as the oceans.

C. Chandler and Annual Wobbles

Studies of the excitation sources for the Chandler and annual wobbles are usually undertaken using Fourier analysis to separate them from other time scales of motion. The annual wobble is a discrete line spectrum, corresponding to 1 cpy forcing of the earth by air and water. The prograde annual wobble, closest to the resonant Chandler period, is most reliably determined because of its good signal to noise level. The retrograde annual wobble in the ILS data is smaller and less reliably estimated (King and Agnew, 1991).

The appropriate way to study the annual wobble is to compare the prograde sinusoidal excitation coefficient determined from the ILS data by least squares, with the predicted sinusoidal component representing the sum of all air and water contributions that can be estimated. The findings of Kuehne and Wilson (1991) confirm those of Chao and O'Connor (1988b), which was that the sum of air mass excitation and continental water storage do not explain observed annual polar motion. The discrepancy is approximately as large in magnitude as the air mass effect, although of a different phase.

The Chandler wobble is a resonant mode of the Earth, probably excited by a broad band excitation source. The standard procedure for Chandler Wobble analysis is to pass the ILS or other polar motion data through a filter which removes the resonant amplification. For example, the digital filter of Wilson (1985) is effective, and, subsequent removal of the annual sinusoid leaves the spectrum suitably flat or "pre-whitened" for Fourier spectral analysis. Following this procedure, Kuehne and Wilson (1991) found that in the vicinity of the Chandler and annual frequencies, the combined effects of air mass and continental water storage were too small, by 6 to 8 decibels, to acount for observed polar motion. Apparently significant coherence near the Chandler frequency at a level of about 0.3 was consistent with the the hypothesis that roughly 25-30% of the variance of polar motion was due to air mass and continental water storage, with the majority due to the air mass effect.

The shortfalls in explaining observed polar motion variance near the annual and Chandler frequencies suggest that either a significant excitation source has been omitted, or that air mass and continental water storage, the two elements for which time series have been computed, are not estimated properly. Kuehne and Wilson suggest that their continental water storage estimate is probably not at fault because in this frequency band the lack of spatial coherence of water storage from basin to basin leaves it unable to contribute effectively to the degree 2, order 1 spherical harmonic shape needed to excite polar motion.

A shortcoming in the air mass calculation is likely to come only in the misapplication of the inverted barometer assumption. This assumption, developed by Jeffreys (1916) to deal with the lack of barometric pressure data over the oceans, treats the oceans as if they are isostatic, so that there is a tendency for sealevel to diminish in response to higher local barometric pressure. It is the general concensus that at annual and lower frequencies, inverted barometer behavior is likely to be a good approximation (Dickman, 1988). At frequencies well above 1 cpy, the inverted barometer assumption may be too simple an approximation, however. (Eubanks et al, 1988)

The discrepancy between observed and predicted polar motion near the annual frequency may be due in part to wind-driven redistribution of mass in the oceans. This is not the only possibility, but it is the least well studied. Other possible contributors include wind and ocean current contributions, as described by Wahr (1983). A theory for wind-driven redistribution of ocean mass was presented by Gill and Niiler (1973), valid for time scales of months and longer. The mechanism is associated with Ekman pumping in which vertical motions in the water, induced by wind stress curl, will lead to divergence and convergence at the bottom, with associated bottom pressure load gradients. Lambeck (1980) reviews the mechanism but suggests that it is too small to be important. More recently, Benedict and Wilson (1990) and Gutierrez (1990) have found that the effect may be important. In particular, Benedict and Wilson showed that for typical mid-Pacific seasonal pressure fluctuations, the Gill-Niiler theory predicted bottom load variations comparable to but opposite in sign to the inverted barometer effect. Gutierrez showed that using the Hellerman and Rosenstein (1983) seasonal wind stress field, the Gill-Niiler theory predicted significant annual wobble and non-steric sealevel changes which could be considered reasonably consistent with observations.

D. High Frequency Motion

The study of Eubanks et al (1988) examined correlations between air mass excitation series and polar motion in the frequency range 1-20 cpy, using space geodetic polar motion series and atmospheric excitations derived from global general circulation models. They found broad band correlations and variance estimates suggesting that half or more of polar motion variance in this frequency range was forced by atmospheric mass redistribution. See Figure 4 for a summary of the variance shortfall. Recent studies (Salstein and Gambis, 1991) confirm the general conclusions for periods as short as several days. There is evidence of correlation between atmospheric-general-circulation-model-derived atmospheric forcing and observed polar motion at the level near 0.5, but there is not a full explanation of variance, nor full correlation.

The ability to observe near- and sub-diurnal polar motion has already been demonstrated and raises several interesting questions. In the first place, the Liouville Equation derivation needs to be re-examined to be sure that low frequency simplifications are not made. Gross (1991) and Dickman (1991) have undertaken this task. Then, the formulation of the excitation functions needs to be reexamined. This has resulted in the work by Gross (1991, in press) which recognizes that the practice of polar motion services in using the celestial ephemeris pole means that the appropriate excitation functions for polar motion observables are the Chi functions of Barnes et al (1983), without the Chi time-rate-of-change terms. With these theoretical and observational tools in hand, the study of near and sub diurnal polar motion has already begun. Among the first results is that tidal motion in the ocean, both currents and heights, is probably an important forcing mechanism for short period polar motion (Dickman, 1991). Departures from inverted barometer behavior are also likely to be significant at the very shortest periods, as well.

3. Discussion

Studies and observations of polar motion to date suggest the following conclusions: The drift of the pole over thousands of years is a forced motion resulting from the effects of post-glacial rebound following the melting of the last Pleistocene ice sheets over 10,000 years ago. Decade scale polar motion is dominated by motion which is linearly polarized along the direction that would result from a simple sea-level rise or fall, suggesting that it is forced by water mass redistribution within the ocean basins. Both the total mass of water contained in the oceans, and redistribution of water among the oceans may contribute to such an excitation. Air mass fluctuations alone seem insufficient in variance and lack full correlation with observed polar motion at Chandler, and higher frequencies. This discrepancy suggests another source which is not likely to be water storage on land. The candidates for the missing excitation are the oceans, the winds, an improper use of the inverted barometer assumption, or some combination of these, perhaps in different proportion at different frequencies. In summary, there is evidence that water contributes significantly to the excitation of polar motion at all observable time scales. At the longest time scales, the geological evidence for the ice melting history, coupled with computation of the viscous response of the earth support this hypothesis directly. At shorter decadal time scales, the evidence is suggested by the longitude along which the motion is polarized. At Chandler, annual and shorter time scales, the evidence is that by a process of elimination, no other candidates seem as likely.

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6.0 Related Technical Activities of Clark R. Wilson

International Association of Geodesy, International Union of Geodesy and Geophysics 1987-1991 Member of Special Study Group on Atmospheric Excitation of the Earth's Rotation; 1991-1995 Member of special Study Group 5.143, Rapid Earth Orientation Variations, 1992 Member of ad hoc IAG Working Group on Global Change.

International Earth Rotation Service, Observatoire de Paris: 1991 Elected Corresponding Member.

Committee on Earth Studies of the Space Studies Board, National Research Council: 1991 appointed to membership