Oceanic Excitation of Polar Motion and Nutation: An Overview

Aleksander Brzezinski

Space Research Centre, Polish Academy of Sciences, Bartycka 18A, 00-716 Warsaw, Poland

Abstract: Exchanges of the angular momentum between the atmosphere, the ocean and the solid Earth have an important impact on polar motion at periods from a fraction of a day to years and contribute significantly to nutation. But while the role of the atmosphere in the excitation balance is well established, the importance of the ocean has been recognized only recently. This paper gives an overview of the non-tidal oceanic excitation of polar motion and nutation by taking into account recent advances in modeling the oceanic angular momentum.

1 Introduction

The coupled system of the atmosphere and oceans has a major impact on polar motion over a broad range of periods via exchanges of the angular momentum with the underlying solid Earth. The role of the atmosphere in the excitation of polar motion has been relatively well quantified, mainly due to the fact that time variations of the atmospheric angular momentum (AAM) are well constrained by the available meteorological observations; see, e.g., (Brzezinski et al., 2002a) for a recent review. The atmosphere, with its mass amounting only to 1 part in 10^2 of the oceanic mass, exhibits strong mobility, forced primarily by the diurnal and seasonal cycles, which causes the corresponding angular momentum changes to be able to exceed those in the ocean.

The oceanic excitation of polar motion does not have as good an observational evidence, although it is expected to be important. If we neglect tidal fluctuations in the ocean, including the so-called pole tide, the remaining variability of the oceanic angular momentum (OAM) is mostly driven by the atmospheric forcing and the thermohaline processes caused by heat and freshwater fluxes. A significant part of the oceanic excitation is the ocean response to the overlying pressure variations which has long been modeled implicitly by adding the so-called *inverted barometer* (IB) correction to the pressure term of the atmospheric angular momentum. This simple static model has proven to be a reasonably good approximation at periods of weeks and longer (Wahr, 1983). Estimating the remaining variability of the OAM, induced by surface winds as well as heat and freshwater fluxes, is much more complicated because it requires three-dimensional modeling of the global ocean dynamics. Only recently have there been successful attempts to produce such data, reported e.g. by Ponte et al. (1998) and Johnson et al. (1999). Further improvements of modeling the OAM, stimulated by the International Earth Rotation Service (IERS) Special Bureau for the Oceans (SBO), are under development.

Here we present an overview of the non-tidal oceanic excitation of polar motion and nutation taking into account recent advances in modeling the oceanic angular momentum. The excitation spectrum is split into seasonal effects, Chandler wobble, and other components of polar motion (intraseasonal, interannual and decadal). Special attention is paid to the non-tidal oceanic effects in the diurnal, subdiurnal and nutation bands which are still largely uncertain due to the lack of appropriate data and models.

2 Seasonal Effects

The seasonal component of polar motion consists of a slightly elliptical annual wobble with amplitude near 90 mas (milliarcseconds) and much weaker higher harmonics: semiannual (<5 mas) and terannual (<1 mas). Each of the seasonal wobbles can be further decomposed into the prograde (counterclockwise) and retrograde components. In case of the annual wobble the prograde component is dominant due to its vicinity to the Chandler resonance – its amplitude is about 30 times larger than that of the retrograde component. It has long been established that the main contribution to the excitation of the annual wobble comes from the atmospheric pressure variation corrected for the IB response of the ocean; see (Eubanks, 1993) for a review of the earlier results and (Brzezinski et al., 2002a) for an estimate based on the NCEP/NCAR AAM reanalysis series. The IB correction plays an essential role in the seasonal band as it reduces the variance of the AAM by the factor of about 3.7 (Brzezinski and Ponte, 2002). The total atmospheric contribution (IB pressure plus wind) to the prograde annual amplitude is only slightly bigger than the observed value, but the difference in phase is rather large, up to 30°.

The oceanic contribution to the seasonal wobbles was studied extensively by Ponte and Stammer (1999) who used the OAM time series derived by Ponte et al. (1998) spanning 1985–1996. In a more recent work, Gross et al. (2002) used substantially longer OAM series spanning 1980–2000 estimated from the output of a different OGCM. They arrived at the same conclusion that in the case of the annual wobble, adding oceanic excitation to that of the atmosphere brings the modeled excitation closer to the observed. The same is also true for most of the semi-annual and ter-annual prograde/retrograde wobbles. But the remaining discrepancy at the seasonal frequencies after removing the atmospheric and oceanic contributions is still significant. That can be partly attributed to errors in the polar motion and atmospheric/oceanic excitation data, but also certainly indicates that other seasonal processes contribute to the seasonal wobbles, such as seasonal variations in soil moisture, snow load, etc. (Eubanks, 1993; Wünsch, 2002), which are not as well constrained by observations as are the AAM and OAM. However, the seasonal excitation budget should be improved considerably after receiving observations from the CHAMP and GRACE satellite missions which will be measuring changes in the Earth's gravitational field caused by mass displacements over the surface of the Earth.

3 Chandler Wobble

The Chandler wobble is a free prograde oscillation in polar motion with a period of $T_C = 14$ month and a variable amplitude with mean value of about $A_C = 160$ mas. This oscillation is subject to damping which is taken into account by expressing the corresponding resonant angular frequency as $\sigma_C = 2\pi F_C (1 + i/2Q_C)$, where $F_C = 1/T_C$ denotes the frequency in cycles per time unit and Q_C is the dimensionless quality factor which is inversely proportional to the wobble energy dissipation rate. An analysis of 100 years of observations of polar motion yields values of Q_C between 150 and 180 which implies that the corresponding dissipation time is between 55 and 68 years. In the absence of excitation, this free wobble should decay during the period of its observation. But this is evidently not the case, which means that there exists a process (or a combination of processes) permanently exciting the wobble.

Table 1 Polar motion excitation on intraseasonal time scales (Nastula and Ponte, 1999)

	periods of 2 to 15 days		periods of 15 to 150 days	
correlation	χ_1: 0.43 ⇒ 0.48	χ_2: 0.54 ⇒ 0.52	χ_1: 0.53 ⇒ 0.80	χ_2: 0.75 ⇒ 0.88
variance (%)	χ_1: 18 ⇒ 38	χ_2: 26 ⇒ 42	χ_1: 45 ⇒ 88	χ_2: 27 ⇒ 49

Global processes taking place in the atmosphere have been considered as a candidate for the excitation of the observed Chandler wobble for a long time – see, e.g., (Eubanks, 1993) for a thorough review of earlier results and (Brzezinski et al., 2002a) for an estimate based on the 50-year NCEP/NCAR reanalysis AAM series. A common conclusion was that the AAM variations provide less than half of the power needed to maintain the observed Chandler wobble, with the dominant contribution coming from the pressure term. (The role of the wind term still remains controversial – see, e.g., Aoyama, paper presented at this Workshop.)

One possible candidate for explaining the remaining large gap in the excitation balance is the ocean. Gross (2000) and Brzezinski and Nastula (2002) investigated this problem using an 11-year OAM series estimated by Ponte et al. (1998). These two works, which used different methods of data analysis, nevertheless arrived at the similar conclusion that the combination of atmospheric and oceanic processes contained sufficient power near the resonant frequency and was highly coherent with the observed Chandler wobble between 1985 and 1996. The ocean-bottom pressure variations appeared to be the single most effective excitation mechanism. These conclusions were confirmed by the recent work of Gross et al. (2002) who used a 20-year OAM series based on a different OGCM.

Our analysis (Brzezinski et al., 2002b) of a 50-year OAM time series estimated by Ponte (2001, private communication) from a different ocean model and data assimilation system, showed again that the OAM contains sufficient power to close the excitation balance of the Chandler wobble; nevertheless, the coherence with geodetic data at the Chandler frequency decreased significantly in comparison to the previous studies. The lower coherence could be partly attributed to the inclusion in the analysis of earlier data of inherently lower quality. But comparison done over the common period 1985–1996 showed significant differences between the two OAM series.

The difference discovered between the OAM series at the Chandler frequency indicates that further improvements in the ocean models and data assimilation systems are still necessary. Comparison with the Earth orientation data is a useful tool in verifying the overall quality of the ocean analyses and checking the reliability of the OAM data.

4 Other Components of Polar Motion

In this section we will consider the ocean excitation of polar motion within the following three frequency bands: (1) intraseasonal – periods from several days to 1 year, excluding seasonal variations; (2) interannual – periods from 1 to 6 years, excluding annual, and (3) decadal – periods longer than 6 years. The role of the ocean will be conveniently expressed by two parameters, the first one expressing the correlation coefficient between the modeled excita-

Table 2 Polar motion excitation on intra-seasonal time scales (Gross *et al*., 2002)

	periods of 5 days to 1 year	
correlation	χ_1: 0.61 ⇒ 0.78	χ_2: 0.69 ⇒ 0.82
variance (%)	χ_1: 37 ⇒ 61	χ_2: 48 ⇒ 67

tion expressed by the sum AAM+OAM and the observed excitation (that is inferred from the polar motion data), and the second one expressing the percentage of the observed excitation variance which can be explained by the modeled excitation. Selected estimates of these two parameters are given in Tables 1–3 for each equatorial component of the excitation separately, and then contrasted to the corresponding quantities computed for the atmospheric excitation alone (the arrows indicate the change from AAM to AAM+OAM).

Intraseasonal periods.

Table 2 gives the results obtained by Nastula and Ponte (1999) for a data span of 1993–1995, and Table 2 gives the results obtained by Gross et al. (2002) for a data span of 1980–2000.

Interannual periods.

Table 3 gives the results obtained by Gross et al. (2002) for a data span of 1980–2000. The dominant contribution comes from ocean-bottom pressure variations.

Table 3 Polar motion excitation on inter-annual time scales (Gross et al., 2002)

	periods of 1 to 6 years	
correlation	χ_1: 0.26 ⇒ 0.40	χ_2: 0.29 ⇒ 0.71
variance (%)	χ_1: 3.5 ⇒ 7.5	χ_2: 6.5 ⇒ 50.8

Decadal periods.

Brzezinski et al. (2002b) and Gross et al. (2002) concluded that neither atmospheric nor oceanic angular momentum has enough power to explain the observed low frequency variation in polar motion, consisting mostly of a 30-year “Markowitz wobble”.

5 Diurnal, Sub-diurnal and Nutation Bands

At diurnal and sub-diurnal periods, the ocean contributes significantly to polar motion by the tidal variations. However, as the global circulation of the atmosphere exhibits strong diurnal and semi-diurnal signals (Brzezinski et al., 2002a), we can also expect that the wind- and pressure-driven ocean variability contains diurnal and semi-diurnal signals. These high frequency sig-

nals in OAM can in turn contribute to the diurnal and semi-diurnal variation in polar motion and, in case of the retrograde diurnal excitation, to nutation. Questions of particular interest have to do with: (1) the oceanic contribution to the nutation amplitudes which can contain both the constant part that should be included in the conventional precession/nutation model and the time-dependent part, (2) the role of the ocean in the excitation of the observed free core nutation signal, and (3) the importance of the non-tidal oceanic contributions to the prograde diurnal and semi-diurnal polar motions. Any research on such problems requires a special kind of OAM data. First, a subdaily (at least 6-hourly) sampling of the OAM is necessary. Second, as the static IB model is not adequate at such high frequencies (e.g., Bizouard et al., 1998), the pressure forcing should be taken into account in the underlying OGCM. Most of the available OAM series do not fulfill these requirements.

The first attempt to assess the effect of the atmospherically driven ocean dynamics on nutation was reported by Petrov et al. (1998) who used the 6-hourly OAM series from a 3-year barotropic model developed by Ponte (1997). An important and promising finding was that the ocean contribution to nutation is of similar size as that of the atmosphere. However, due to the relatively short data span and much higher noise contents than in the AAM, they could detect in the OAM data only the S_1 wave corresponding to the prograde annual nutation. After accounting for the OAM, the agreement with the VLBI nutation data became worse in comparison to the pure atmospheric non-IB effect. One reason for that, pointed out by Ponte (1998, private communication), was that the corresponding OGCM was not reliable in the diurnal band due to its sensitivity to some poorly constrained parameters such as bottom friction coefficient. A possible criterion of constraining these parameters is to minimize the difference between the atmospheric plus oceanic excitation and that inferred from the VLBI observations.

6 Summary and Conclusions

Recent estimates of non-tidal oceanic angular momentum demonstrate the importance of ocean dynamics in driving polar motion at seasonal, intraseasonal and interannual periods. Adding the OAM to the AAM brings the modeled excitation closer to the observed; nevertheless the remaining discrepancy is still significant. Particularly important are results concerning the excitation of the free Chandler wobble. Several independent works demonstrated that the combination of atmospheric and oceanic processes contains sufficient power near the resonant frequency and is highly coherent with the observed free wobble. At periods longer than 6 years the OAM, similarly as the AAM, contains too little power to explain the observed variability in polar motion. At diurnal and subdiurnal periods, including the nutation band, the role of the OAM still remains uncertain due to the lack of appropriate data and models.

This brief review shows that the following two tasks related to the activity of the IERS SBO are important for a better understanding of the oceanic excitation of polar motion and nutation: (1) further improvements in both the model and data assimilation systems used to estimate the OAM series, and (2) development of the ocean circulation models which enable estimation of the OAM series containing high frequency signals, up to the semi-diurnal band.

Acknowledgements

I thank R. Gross for carefully proofreading the manuscript and for improving the grammar. This research has been supported by the Polish National Committee for Scientific Research (KBN) under grant No. 8 T12E 005 20.

References

Bizouard, Ch., A. Brzezinski, and S. Petrov, Diurnal atmospheric forcing and temporal variations of the nutation amplitudes, *J. Geodesy*, **72**, 561–577, 1998.

Brzezinski, A., and J. Nastula, Oceanic excitation of the Chandler wobble, *Adv. Space Res.*, **30**, 195–200, 2002.

Brzezinski, A., and R. Ponte, Non-tidal oceanic excitation of nutation and high frequency polar motion estimated from a barotropic ocean model, *Geophys. Res. Abs.*, **4**, Abstract No. EGS02-A-04770, 2002.

Brzezinski, A., Ch. Bizouard, and S. Petrov, Influence of the atmosphere on Earth rotation: What new can be learned from the recent atmospheric angular momentum estimates?, *Surveys Geophysics,* **23**, 33–69, 2002a.

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, 2002b.

Eubanks, T. M., Variations in the orientation of the Earth, in *Contributions of Space Geodesy to Geodynamics: Earth Dynamics*, edited by D. E. Smith, and D. L. Turcotte, pp. 1–54, American Geophysical Union Geodynamics Series, Washington, D.C., 1993.

Gross, R. S., The excitation of the Chandler wobble, *Geophys. Res. Lett.*, **27**, 2329–2332, 2000.

Gross, R. S., I. Fukumori, and D. Menemenlis, Atmospheric and oceanic excitation of the Earth's wobbles during 1980–2000, *J. Geophys. Res.*, submitted, 2002.

Johnson, T. J., C. R. Wilson, and B. F. Chao, Oceanic angular momentum variability estimated from the Parallel Ocean Climate Model, 1988–1998, *J. Geophys. Res.*, **104**, 25183–25195, 1999.

Nastula, J., and R. M. Ponte, Further evidence for oceanic excitation of polar motion, *Geophys. J. Int.*, **139**, 123–130, 1999.

Petrov, S., A. Brzezinski, and J. Nastula, First estimation of the non-tidal oceanic effect on nutation, *Proc. Journées Systèmes de Référence Spatio-Temporels 1998*, Paris Obs., 136–141, 1998.

Ponte, R. M., Oceanic excitation of daily to seasonal signals in Earth rotation: Results from a constant-density numerical model, *Geophys. J. Int.*, **130**, 469–474, 1997.

Ponte, R. M., and D. Stammer, Role of ocean currents and bottom pressure variability on seasonal polar motion, *J. Geophys. Res.*, **104**, 23393–23409, 1999.

Ponte, R. M., D. Stammer, and J. Marshall, Oceanic signals in observed motions of the Earth's pole of rotation, *Nature*, **391**, 476–479, 1998.

Wahr, J. M., The effects of the atmosphere and oceans on the Earth's wobble and on the seasonal variations in the length of day – II. Results, *Geophys. J. Roy. astr. Soc.*, **74**, 451–487, 1983.

Wünsch, J., Oceanic and soil moisture contributions to seasonal polar motion, *J. Geodynamics*, **33**, 269–280, 2002.