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► **To cite this version:**

Sébastien Lambert, Christian Bizouard, Véronique Dehant. Rapid variations in polar motion during the 2005-2006 winter season. *Geophysical Research Letters*, 2006, 33, pp.13303. 10.1029/2006GL026422 . hal-03785260

**HAL Id: hal-03785260**

**<https://hal.science/hal-03785260>**

Submitted on 21 Oct 2022

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## Rapid variations in polar motion during the 2005–2006 winter season

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Received 27 March 2005; revised 19 May 2006; accepted 24 May 2006; published 1 July 2006.

[1] The terrestrial motion of the Earth's rotation pole shows mainly two large oscillations: the Chandler and the annual wobbles driven by mass redistributions in surface geophysical fluids. These contributions interfere destructively every 6.4 years, slowing down the pole at that period of time. This is the case for the recent period from November 2005 till February 2006. Due to the high precision of Earth orientation data of these days and for the first time in the history of polar motion observation, very small structures of the motion are observed. We compared the observed polar motion with the contribution of atmosphere and oceans predicted from global atmospheric and oceanic analyses and models. We clearly see that centimeter level polar motion displacements during the 2005–2006 winter season are almost fully explained by major pressure events on the continents and on the ocean, especially a depression over Northern Europe in-phase with similar events over North America. **Citation:** Lambert, S. B., C. Bizouard, and V. Dehant (2006), Rapid variations in polar motion during the 2005–2006 winter season, *Geophys. Res. Lett.*, 33, L13303, doi:10.1029/2006GL026422.

### 1. Introduction

[2] The Earth's rotation is not regular. The position of the pole undergoes variations on timescales running from a few minutes to billions of years. At yearly time scales, the displacement of the pole shows two major components: (i) a free Eulerian wobble known as the Chandler wobble with period of about 433 days and amplitude up to 300 milliarseconds (mas), and (ii) an annual oscillation forced by the seasonal displacement of air and water masses (amplitude around 100 mas). Every 6.4 years, annual and Chandler wobble interfere destructively. The polar motion, usually 2–6 mas/day (6–18 cm/day), slows down to 1 mas/day (<3 cm/day), and is reduced to the sub-seasonal components. Irregular variations usually masked by the faster motion show up and become observable.

[3] Such a situation has been occurring since November 2005: fast polar motion almost disappears for the benefit of high frequency features, that are loops having radius from 1 to 5 mas, taking place over 1–2 weeks (see Figure 1). Given the Very Long Baseline Interferometry (VLBI) observing schedule (with 3 or more stations involved) of twice sessions per week, VLBI cannot detect loops with weekly periods. But they are perfectly detectable with Global Navigation Satellite Systems (GNSS), with a current accuracy of about 0.05 mas. A similar loop was observed for the

first time on 9–24 December 1999, during the former minimum in polar motion amplitude, less spectacular than the present one. Previous striking minimum in polar motion, before December 1999, goes back to 1980–1981. During this period, some undulations in the pole coordinates seem to exhibit the preponderance of weekly variations, but the observational accuracy, then of the order of 2 mas, did not permit the resolution of such fine structures.

[4] Rapid polar motion was first studied by *Eubanks et al.* [1988]. The authors showed that it was caused in part by the atmospheric variations. However, no oceanic data were available at this time but they speculated that the ocean would make a sizable contribution. The development of atmospheric and oceanic global circulation models provides now subdaily estimates of the atmospheric angular momentum and twice daily values for the oceanic angular momentum. Though the mechanisms of excitation of the Chandler and annual oscillations have been extensively studied in the past years [see, e.g., *Gross*, 2000], as well as for other cyclic variations in the seasonal, decadal and diurnal frequency bands [see, e.g., *Lambeck*, 1980; *Brzeziński et al.*, 2004], it is still of great interest to investigate the interaction between geophysical excitation processes and solid Earth at intermediate time scales (typically a few days). Indeed, one could wonder what happens on the pole position when, for instance, a heat wave strikes a limited geographical area, or a very strong winter depression batters Siberia or Canada? More generally, are we able, with the current level of capability of the Earth monitoring techniques and the current atmospheric and oceanic data sets, to observe directly the effects of continental-scale meteorological phenomena on the Earth's rotation?

[5] Challenging questions arise then concerning operational activities like the short-term prediction of Earth orientation parameters done at the Earth Orientation Center (Paris Observatory) and the Rapid Service/Prediction Center (US Naval Observatory, Washington, DC) of the International Earth Rotation and Reference Systems Service (IERS). In this paper, we present recently directly observed very fine structures in polar motion. We establish their respective links with local meteorological phenomena.

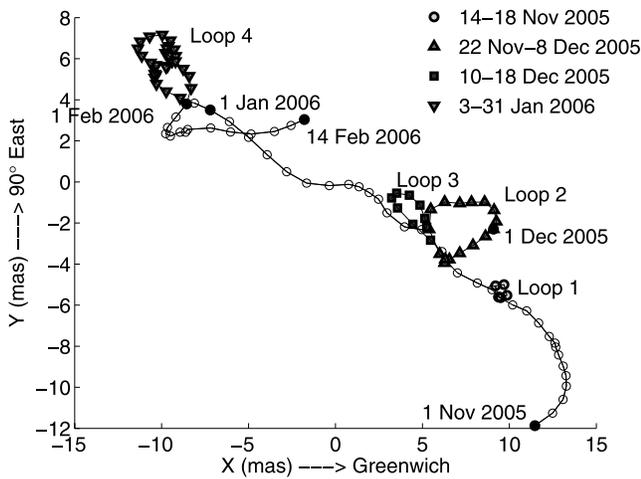
### 2. Motion of the Earth's Pole and Fluid Forcing

[6] The complex pole coordinates  $p = x - iy$  ( $x$  being toward the Greenwich meridian and  $y$  being positive by convention toward  $90^\circ\text{W}$ ) in the terrestrial frame induced by variations in a fluid layer angular momentum are given in the time domain and for seasonal or sub-seasonal timescales by [see, e.g., *Barnes et al.*, 1983]:

$$p + i \frac{\dot{p}}{\sigma_{\text{cw}}} = \frac{H_{\text{pressure}} + 1.43H_{\text{motion}}}{(C_m - A_m)\Omega} \quad (1)$$

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**Figure 1.** Motion of the pole following the IERS C 04 combined series from 1 November 2005 (bottom-right boundary) to 14 February 2006. Five loops are identified with different markers. Dark circles indicate the beginning of each month corresponding to the civil date written nearby.

where  $\sigma_{cw}$  is the complex Chandler wobble frequency and  $C_m$  and  $A_m$  the axial and equatorial mean moments of inertia of the mantle. The right-hand side of (1) is the so-called excitation function proportional to the fluid layer angular momentum  $H = H_x + iH_y$ , itself split into two parts accounting for the respective contributions of matter (or pressure) and motion. The left-hand side of (1) is deduced from observed positions of the pole and constitutes the geodetic excitation. Following equation (1), and for weekly frequencies, an increment of excitation in a given direction shifts the pole in the negative direction. Note that, for these time scales, the error on the geodetic excitation function can be deduced from the observational error and is around 0.7 mas.

[7] Ocean bottom pressure variations include (i) the response of sea water to variations in atmospheric pressure and (ii) changes due to variations in the salinity and temperature. For the former point, one assumes generally that, for time scales larger than a few days, the deformation of sea surface induced by atmospheric pressure variations is canceled out by a redistribution of sea water. This redistribution leads to a readjusted pressure on ocean bottom. In this case, the oceans are said to be behaving as an inverted barometer (IB). Non IB (NIB) ocean is assumed for time scales around and below a few days. In this hypothesis, oceans do not react to any atmospheric pressure variations and any increment in the atmospheric sea level pressure is fully and instantaneously transmitted to the ocean bottom. The IB or NIB hypotheses are considered as extreme hypotheses.

[8] Practically, polar motion is observed mostly (about 80%) through GNSS, helped by VLBI and SLR measurements. The current precision is such that motions of the pole of the order of a centimeter over a few days can be considered with a high level of significance. Due to the large amount of GNSS in the combination for polar motion calculation, this precision will further increase with the modernization of GPS and the new GALILEO system.

[9] Combined series IERS EOP C 04 produced at the IERS Earth Orientation Center (Paris Observatory), reflects the ability of GNSS to capture such thin structures in polar motion. For polar motion about 80% of the observations come from six operational GPS/GLONASS series, and the last 20% is shared between SLR and VLBI measurements. C04 and GNSS series show differences at the level of 30 microarcseconds ( $\mu\text{as}$ ), with some systematic biases up to 300  $\mu\text{as}$  due to the fact that these series are not referred to the same terrestrial frame. Present accuracy on pole coordinates reaches 50  $\mu\text{as}$ .

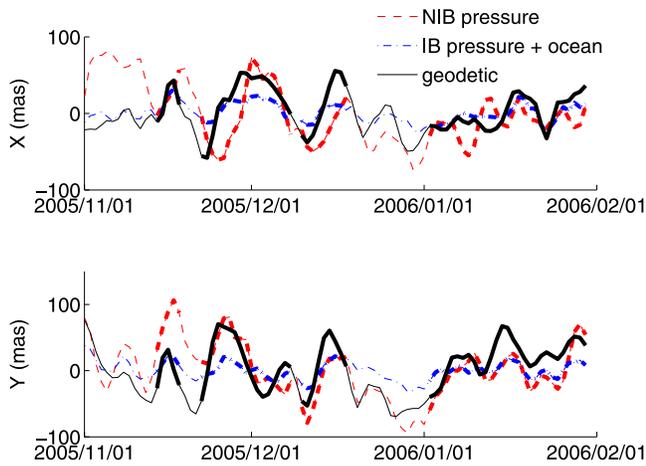
[10] Figure 1 depicts the polar motion from 1 November 2005 to 14 February 2006 given the IERS C 04 series, and the loops, as described, are easily seen. According to what is stated in the previous paragraph, there is no doubt for the reality of these observed loops.

[11] Concerning the geophysical fluid excitation, we use daily uniform grids of surface pressure fields provided by the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis project [Kalnay *et al.*, 1996]. Atmospheric angular momentum both under IB and NIB hypotheses are provided by the Special Bureau for the Atmosphere (SBA), which computes the atmospheric surface pressure contribution to the atmospheric angular momentum [Salstein *et al.*, 1993]. Ocean bottom pressure fields output from the oceanic model ECCO-2 [Fukumori *et al.*, 2002] are used to get estimates of the oceanic angular momentum during the relevant time period. ECCO-2 employs the MIT global circulation model in a near-global domain from 78°S to 78°N. The model is forced by NCEP/NCAR reanalysis products (12-hourly wind stresses, daily adiabatic air-sea fluxes). Temperature and salinity of the model sea surface are further relaxed toward observed values. Sea level anomalies (e.g., TOPEX/Poseidon, XBTs) are assimilated into the model to correct errors associated with inaccuracies in time-varying wind forcing. The data sets are made available through the IERS Global Geophysical Fluid Center (GGFC) Special Bureau for the Oceans (SBO, chaired by R.S. Gross at JPL, Pasadena).

[12] We limit our study to the pressure terms of atmospheric and oceanic angular momentum. The reason is that (i) winds contribute only marginally (less than 20%) in the total atmospheric excitation, and (ii) daily velocity fields are not available for ECCO-2 model. The effects of the oceanic currents, although they are expected to be marginal in the context of this study, will be investigated elsewhere.

### 3. Climatic Events of the 2005–2006 Winter Season

[13] A time domain comparison of the geodetic, atmospheric pressure and ocean bottom pressure excitations is shown on Figure 2. The time periods corresponding to the loops mentioned on Figure 1 are represented in bold lines. It appears that, before the beginning of 2006, the atmosphere along with a “rigid” (NIB) ocean better account for the observed polar motion than the IB atmosphere, of which the power is at least two times weaker, yielding that the atmospheric pressure variations are acting mainly over the oceans. However, variations of the geodetic excitation after the beginning of 2006 are better explained by the



**Figure 2.** Time domain representation of the geodetic, atmospheric NIB and combined atmospheric IB plus oceanic excitation functions. The parts in bold lines indicate the time periods corresponding to the loops observed on Figure 1.

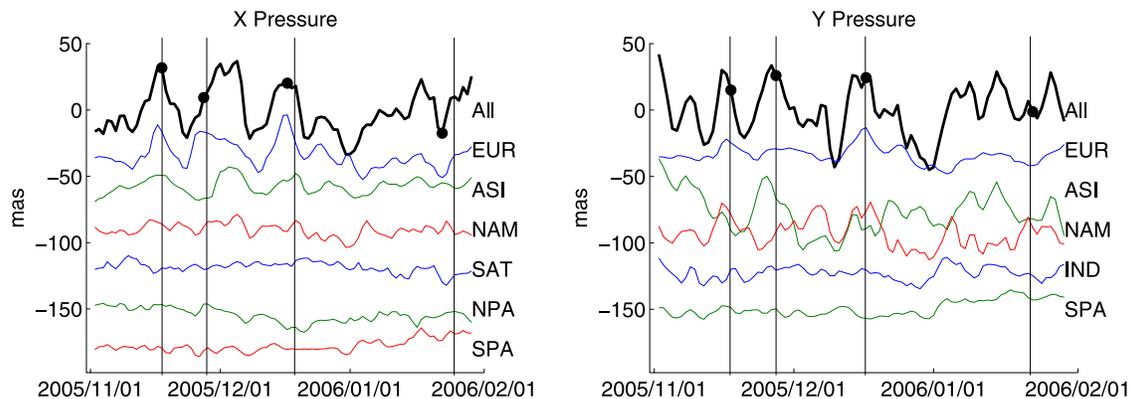
combination of IB atmosphere plus oceans (i.e., including both atmosphere and ocean dynamics). Nevertheless, the coupled system atmosphere + oceans almost fully accounts for the observed variations in the geodetic excitation. Checking simultaneously both IB and NIB assumptions, one sees that the reality, for the weekly time scales, lies in between these two extremes.

[14] The explanation of the retrograde motions occurring during last months visible on Figure 1 shows up clearly: they are due to peaks of excitation occurring simultaneously, or with a slight offset of a few days, on each component, pushing alternatively the pole in one direction and, just later, in a perpendicular direction. As it can be seen on Figure 2 the excitation is starting to increase on  $y$  one or two days before starting to increase on  $x$ , resulting thus in a retrograde variation in the excitation function, producing a displacement of the pole which is also retrograde, as expected by looking at equation (1) in the frequency domain.

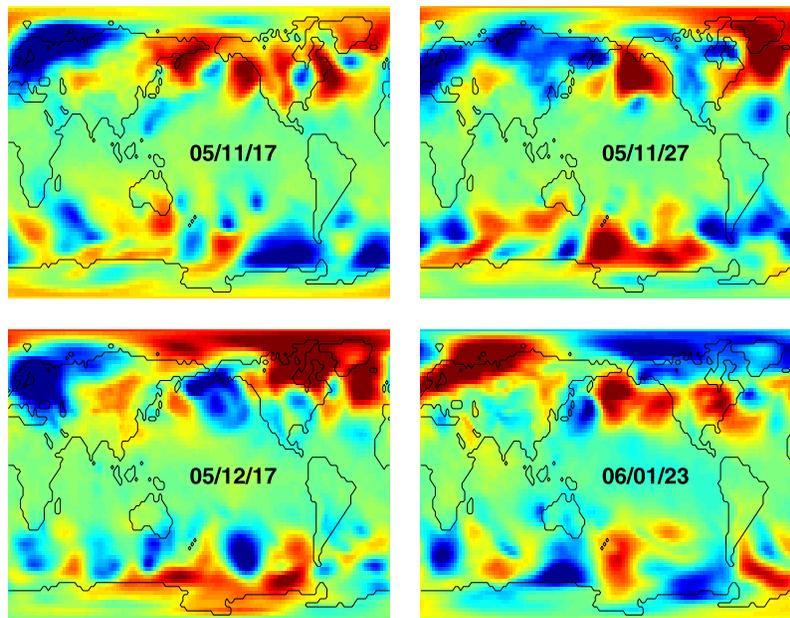
[15] Respective contributions of the different continental and oceanic regions in the global atmospheric and ocean excitation have been computed separately. The aim is to identify, if possible, which low-pressure or high-pressure zone causes the loops, partly or fully. The relevant time period after 1 November 2005 is plotted on Figure 3. Marginal contributions of Africa, South America, Australia, Antarctica, Greenland and North Atlantic are not represented. Note that the contributions in the ocean come mainly from temperate latitude, since the contribution of the tropical band (roughly speaking, consider the zone between  $35^{\circ}\text{S}$  and  $35^{\circ}\text{N}$ ) remains non significant. We selected then charts showing the pressure anomaly, i.e., the pressure field from which the mean pressure field over the complete time period has been removed to suppress permanent effects over seasonal ones. The fields are shown on Figure 4 for four dates we think to show the most representative pressure distributions during the loops.

[16] Note that the variation of angular momentum induced by surface (or ocean bottom) pressure variations is given by the integral of  $P_s(\vec{r}) (\vec{r} \times (\vec{r} \times \vec{\omega}))$ , where  $P_s$  is the surface pressure at the Earth surface point  $\vec{r}$ , and  $\vec{\omega}$  the Earth's rotation vector. This means that a low or a high pressure area does not act in the same way following its location on the Earth. Given that, looking at Figures 3 and 4, the peaks of excitation detected in the European contribution around 17 November 2005 (loop 1), 27 November 2005 (loop 2) and 17 December 2005 (loop 3) are clearly linked to the globally unbalanced low pressures above this region. Inversely, the globally unbalanced high pressure on Northern Europe on 23 January 2006 (loop 4) is contributing in the suddenly low excitation.

[17] But the European climate does not act alone. It is helped by similar scale pressure anomalies in diametrically opposite areas. To achieve the same excitation, high and low pressure areas should be disposed like white and black boxes on a chessboard but separated by  $180^{\circ}$ . By basic considerations on the dynamic of an ellipsoid, one can see that low pressures on Europe and South Pacific will produce an effect in the same direction. Similarly, high pressures on North Pacific and South Atlantic/Indian ocean will contribute too. For instance, the bump of excitation on



**Figure 3.** Local continental and oceanic contributions to the global atmospheric plus oceanic pressure excitation on (left)  $x$  and (right)  $y$ . EUR: Europe, ASI: Asia, NAM: North America, SAT: Southern Atlantic, NPA: Northern Pacific, SPA: Southern Pacific, IND: Indian Ocean. Vertical lines indicate from left to right respectively 17 November 2005, 17 December 2005 and 23 January 2006.



**Figure 4.** Surface and sea level pressure anomaly for four dates representative of time periods during which loops are observed in polar motion. Colors are saturated at  $-20$  (blue) and  $+20$  mbar (red) around the mean value.

22 November–8 December 2005 (loop 2) shows a significant participation of Asia on  $y$  likely due to a large low pressure field on the northern part of this continent while the bumps occurring on 14–18 November 2005 (loop 1) and 10–18 December 2005 (loop 3) on the same component are mainly driven by high pressure fields over North America.

[18] Finally, continental-scale meteorological phenomena, clearly seen in pressure fields obtained through general circulation models and assimilation of data, are able to explain centimeter-scale motions unprecedentedly observed in the Earth's pole displacement. To conclude this discussion, we note that the accuracy and the significance of observed polar motion, as well as atmospheric and oceanic data (all these data sets being provided within the framework of the IERS centers) are really remarkable as it is assessed in this study.

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