ANNALI DI GEOFISICA, VOL. 42, N. 4, August 1999

Chandler wobble excitation by catastrophic flooding of the Black Sea

Giorgio Spada (1) (2), **Laura Alfonsi** (1) **and Enzo Boschi** (1) (3)
(1) *Istituto Nazionale di Geofisica, Roma, Italy*
(2) *Università di Urbino, Istituto di Fisica, Urbino, Italy*
(3) *Università di Bologna, Dipartimento di Fisica - Settore Geofisica, Bologna, Italy*

Abstract

It is now widely accepted that during the late Quaternary glaciation the Black Sea formed an isolated inland lake (Ross *et al.*, 1970). New geological data and the recognition of sudden population movements away from the Black Sea coasts suggest that the basin was rapidly flooded through the Bosphorus sill 7150 years bp, causing a sea level rise of ~ 135 m in a few years (Ryan *et al.*, 1997). As shown here, such a catastrophic redistribution of mass has significantly altered the amplitude of the Chandler wobble, the free motion of the pole of rotation around the main inertia axis of the Earth (Lambeck, 1980). We also estimate that during the flooding the pole of rotation was diverted from its secular path and shifted by ~ 30 m, at a rate of several meters per year. These rotational variations are found to be orders of magnitude larger than those produced by other short-term geophysical processes, such as earthquakes seismic moment release (O'Connell and Dziewonski, 1979; Chao *et al.*,1996), anthropogenic water impoundment (Chao, 1995), and tectonic mass movements (Alfonsi and Spada, 1998). The Black Sea flooding may thus be responsible for the most drastic change in the rotational parameters of the Earth in the recent history of our planet.

Key words *Chandler wobble – Black Sea*

1. Introduction

The source of excitation of the Chandler wobble, the free oscillation of the pole of rotation of the Earth around the main inertia axis (Lambeck, 1980), is still a matter of debate. It is possible that the wobble is continuously maintained against damping by various processes, like atmospheric variability (Wilson and Haubrich, 1976), seismic moment release due to large earthquakes (O'Connell and Dziewonski, 1979), core-mantle interactions (Hide, 1977), and aseismic mass movements (Alfonsi and Spada, 1998). In addition to these geophysical phenomena, which have plausibly characterized the entire history of the Earth, we show that the wobble may be sporadically reactivated by catastrophic events, like the rapid flooding of the Black Sea testified by recent geological documentations (Ryan *et al.*, 1997; Mestel, 1997).

Sediment core data and high-resolution seismic profiles (Ryan *et al.*, 1997) have led to a surprising result: about 7150 years before present the formerly insulated and partially evaporated Black Sea basin was suddenly flooded through the Dardanelles. During the drowning, ~ 100 000 km^2 of exposed continental shelf were engulfed with a consequent sea-level rise of ~ 135 m in a few years (Ryan *et al.*, 1997). The study by Ryan *et al.* (1997), strongly supports the idea of

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Mailing address: Prof. Giorgio Spada, Università di Urbino, Istituto di Fisica, Via di S. Chiara 27, 61029 Urbino (PS), Italy; e-mail: spada@axub02.fis.uniurb.it

a catastrophic event, as opposed to a previous interpretation (Degens and Ross, 1972; Deuzer, 1972) that implies a gradual basin refilling between 9000 and 7000 bp. The catastrophic scenario is also suggested by paleobiological studies (Wall and Dale, 1974; Fairbanks, 1989) and archeological traces that support a rapid flood (Sokal *et al.*, 1991; Kerr, 1998). Further studies are needed to finally prove or disprove the catastrophic scenario. However, imagine now that the Black Sea flooding occurred with the time and duration suggested by Ryan *et al.* (1997). We propose that besides the geological and cultural alterations, the flooding caused imperceptible effects which are nonetheless of great importance in geophysics, namely a remarkable reactivation of the Chandler wobble (Lambeck, 1980).

The geophysical processes acknowledged as plausible candidates to perturb the Earth's rotation (Lambeck, 1980) only account for very modest variations, possibly detectable by high-precision geodetic measurements. In the case of the Black Sea we face an exceptional excursion of the pole, as large as tens of meters if the basin was completely refilled in a few years (Ryan *et al.*, 1997).

The short time-scale which characterized the flooding, combined with the huge amount of water mass involved (Ryan *et al.*, 1997), is crucial in view of its effects on the rotational signatures of the Earth. In fact, slowly evolving processes such as the readjustment of the Earth's surface in response to the Pleistocene deglaciations (Peltier, 1974) or the mass redistribution associated with mantle convection (Spada *et al.*, 1992; Steimberger and O'Connell, 1997) can only drive slow secular drifts of the pole of rotation, without affecting the amplitude of the Chandler wobble (Ricard *et al.*, 1993).

The time-dependent position m of the pole of rotation during the Black Sea flooding can be studied by means of the linearized Liouville equation (Munk and MacDonald, 1960; Lambeck, 1980), obtained by imposing the conservation of the angular momentum of the Earth. For an elastic Earth, its complex form is (Lambeck, 1980)

$$\frac{i}{\sigma}\frac{dm}{dt}+m=\Psi, \tag{1.1}$$

where σ is the frequency of the Chandler wobble, $m = (\omega_x + i\omega_y)/\Omega$, and ω_x and ω_y are the components of the angular velocity (of modulus Ω) in an Earth-fixed cartesian frame. The excitation function Ψ, which simply represents the position of the mean pole in the x-y plane (Lambeck, 1980), accounts for all of the factors which could perturb the rotational motion, including angular momentum transfer and mass redistribution.

2. Data analysis and discussions

The rotational effects of the flood can be modeled by means of a schematic excitation function represented by a ramp-shaped time-history (Lambeck, 1980). Before the water invasion, supposed to begin at time $t = 0$, the excitation function is simply $\Psi = 0$. Assuming a constant inflow rate during a lapse of τ years, we write $\Psi = \chi \cdot (t/\tau)$ for $0 < t < \tau$, where χ is the final function attained for $t > \tau$. To evaluate χ, we have assumed that a water mass of $\sim 6 \times 10^{16}$ kg is subtracted by a uniform ocean and placed at colatitude $\theta_c = 43.4°$ and longitude $\phi_c = 34.5°$, corresponding to the center of the basin. The mass estimate given above is consistent with a sea-level rise of 135 m (Ryan *et al.*, 1997). We have verified that a more accurate estimate of χ, which accounts for the geometrical details of the load (Vermeersen *et al.*, 1994), does not differ significantly from that obtained here.

Using the numerical values above, our estimate of χ corresponds to an excursion of the mean rotation axis of $\sim 10^3$ mas with respect to its initial position (1 mas is equivalent to $\sim$ 3 cm on the Earth's surface). The pole is shifted towards 145°W, in a direction opposite to the Black Sea. The geographical location of the Black Sea, close to 45°N, makes the mass redistribution particularly effective in driving polar motion variations, since it maximizes the amplitude of Ψ (Steinberger and O'Connell, 1997).

We now quantify the wobble excitation driven by the flooding. Figure 1 shows the ratio $F = a'/a$, where a' and a are the amplitudes of the wobble after and before flooding, respectively. The ratio F, directly derived from eq. (1.1), is plotted as a function of the flood duration τ. Since the amplitude of the wobble before

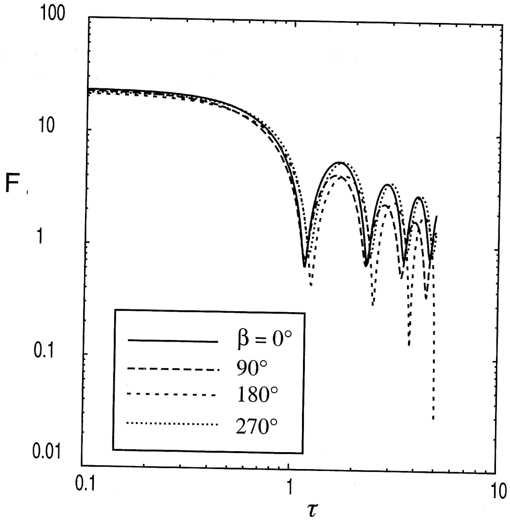

Fig. 1. Plot of $F = a'/a$, where a' is the wobble amplitude after the end of flooding, and $a = 50$ mas is the assumed initial amplitude. The ratio F is plotted as a function of τ, the duration of the flooding process, for various values of β which determines the initial position of the pole. For $F > 1$, the wobble is excited, whereas for $F < 1$ the radius of the final loop is decreased. The amplification F is exactly equal to 1 for values of τ which are integer multiples of the Chandler wobble period T_w. The largest amplifications of the wobble are attained for $\tau < T_w$, and with increasing τ the efficiency of flooding to excite the wobble is generally smaller. However, even for $\tau > 2$ years, there are initial configurations of the pole which allow for significant amplifications of the wobble.

flooding is not known to us, we assume $a = 50$ mas, equal to the mean amplitude of the wobble during the present century (Lambeck, 1980), and explore the effects of varying the initial position of the pole in the x-y plane, defined by the phase angle β. The maximum degree of excitation, with $F \sim 20$ is reached for a flood that occurs in few months, a small time span if compared to the Chandler wobble period $T_w = 2\pi/\sigma \simeq 1.2$ years. For τ close to T_w, F takes its smallest amplitude, to indicate that in this case the water impoundment is ineffective to excite the wobble. This holds also for rise times which are integer multiples of T_w. For rise times of a few years, corroborated by geological data (Ryan *et al.*, 1997), the amplitude of the wobble may increase by a factor between 1 and 5, depending on the value of β. However, other situations are possible, in which the amplitude of the wobble is decreased by flooding, with $F < 1$.

Details on the pole path before, during, and after the water inflow are shown in fig. 2a-d, where the initial amplitude of the wobble and the angle β are kept fixed to 50 mas and 0°, respectively. Each panel refers to distinct rise times, the variable which mostly affects the amplitude of the perturbed wobble (see fig. 1). In the whole set of panels, open circles denote the tip of the excitation function Ψ, whereas the position of the pole m is marked by filled circles. Labels 0, 1, and 2 refer to times $t = 0$, $t = \tau/2$, and $t = \tau$, respectively. The initial position of the excitation function, not shown for the sake of clarity, is always located at point (0,0). The pole path is circular before time $t = 0$ and at the end of the process ($t > \tau$). The length of Ψ_2 does not depend on τ, but only on the load amplitude, while the rate of polar drift scales with τ^{-1}.

In fig. 2a the load is activated on a relatively short time-scale, $\tau = 0.5$ years. In this case the pole reaches the final circular loop very quickly, with a drift rate of tens of meters per year during flooding, and the amplitude of the wobble is magnified by a factor of ~ 10 with respect to its initial value. In panel (b), where the rise time equals the period of the Chandler wobble, the amplitude of the wobble is not altered and the initial circular pole path is simply shifted by an amount equal to Ψ_2. For time scales akin to those suggested by recent geological evidence (Ryan *et al.*, 1997), we still observe an amplitude increase (c,d), accompanied by a slower drift of the mean pole. Now the pole moves along winding paths before reaching a final state of equilibrium. In these two situations, the wobble is magnified by a factor of ~ 4 and ~ 2, respectively.

To fully appreciate the impact of the Black Sea flood on Earth rotation, we can compare the above changes with those due to other geophysical phenomena both in terms of Chandler wobble excitation and polar drift. The excitation function due to the 1960 Chilean earthquake, the largest seismic event of this century (McCarthy and Luzum, 1996), has been theo-

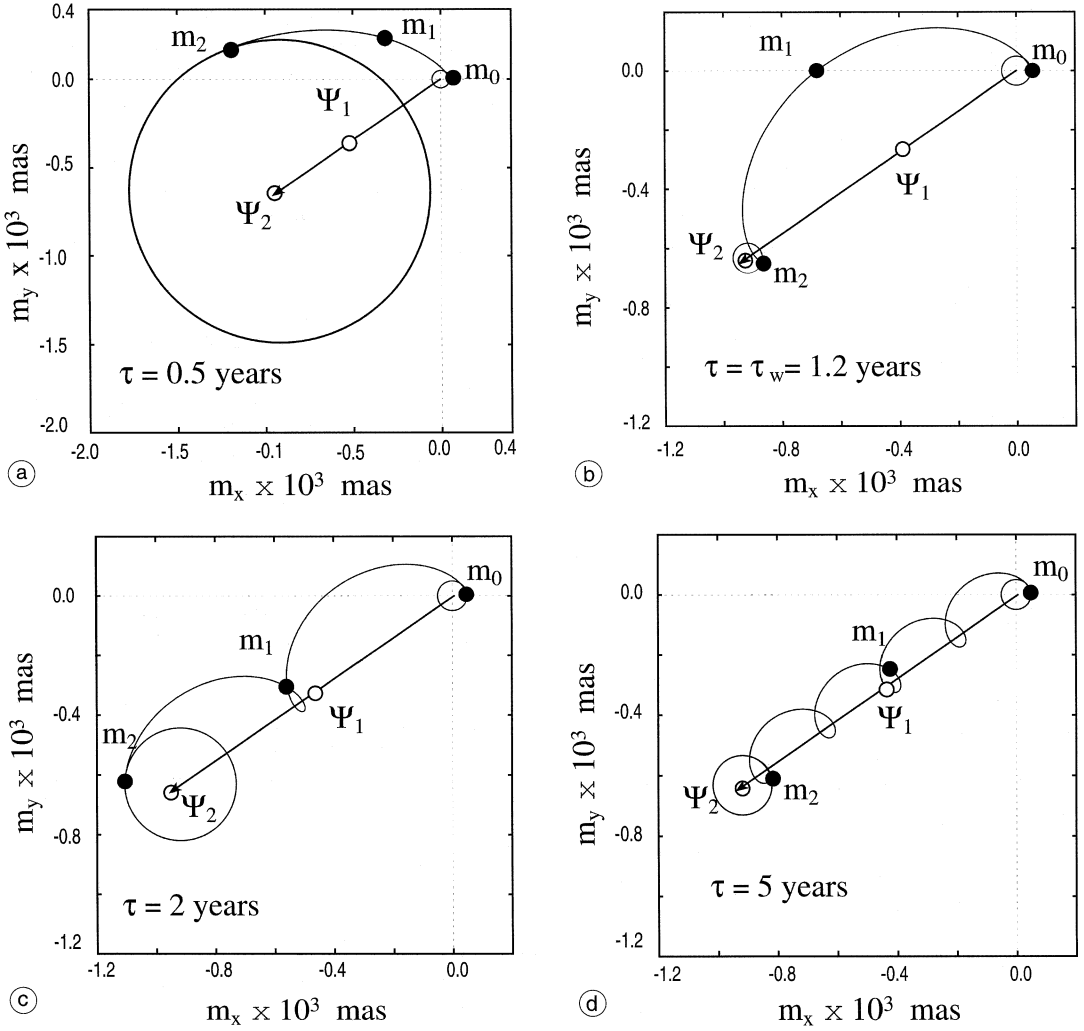

Fig. 2a-d. Excursions of the instantaneous pole of rotation driven by the Black Sea flood, assuming four distinct rise times τ. With m_0, m_1, and m_2 we denote the positions of the pole at times $t = 0$, $\tau/2$, and τ, respectively. The same also applies to the excitation function Ψ. Ψ_0, not shown here, is always located in the origin the axes frame. We always assume that the pole of rotation is initially at $m_0 = (50, 0)$ mas. The length of Ψ_2 is 10^3 mas in each panel. The x and y axes range between -1.8 and 0.4×10^3 mas in panel (a), and between -1.2 and 0.2×10^3 mas in the other frames (b, c, d).

retically estimated as 22.6 mas in the direction 115°E (Gross and Chao, 1990). Assuming an instantaneous release of seismic moment, we find that for this earthquake the wobble amplification F amounts to 1.25. A slightly smaller value is obtained for the 1964 Alaska earthquake, with F = 1.14. These ratios are much smaller than those obtained for the Black Sea, even when flooding occurs in 2-5 years, with F ranging between 2 and 4 (see fig. 2c,d).

The Black Sea rapid drowning has produced a considerable rate of drift of the rotation axis. According to our calculations, if the sea-level rise is assumed to take place in a few years, it amounts to ~ 10 m/year (see fig. 2a-d), approximately 10 times larger than the currently observed secular rate (McCarthy and Luzum, 1996). There is no comparison between the drift rate driven by Black Sea flooding and those by other geophysical phenomena, *e.g.* anthropogenic water impoundment during the last 40 years (2×10^{-2} m/year, Chao, 1995), global seismicity during 1977-1997 (0.2×10^{-2} m/year, Chao *et al.*, 1996; Alfonsi and Spada, 1998), and tectonic movements along plate margins on a decade time-scale (0.2×10^{-2} m/year, Alfonsi and Spada, 1998).

3. Conclusions

The drastic changes in the Earth's rotation due to the Black Sea flooding have been quantified on the assumption that the basin was catastrophically submerged over a very short lapse of time (Ryan *et al.*, 1997). It is plausible that, before the Mediterranean broke through the Bosphorus channel, the pole of rotation was under the influence of the inertia changes due to the melting of the Laurentian and Fennoscandia ice sheets. According to post-glacial rebound studies (Peltier, 1982), the pole was wandering towards the center of mass of the previously existing ice domes, in the direction of Greenland. The Black Sea flooding may have temporarily diverted the pole from its secular path, causing a very fast drift along a direction roughly perpendicular to Greenland. At the same time, the wobble may have been subject to a sizeable amplification, that could amount up to a factor of ~ 4. Finally, after the end of the process, this reactivated wobble relaxed to the initial amplitude in a few decades due to mantle anelasticity (Lambeck, 1980).

Although the source of excitation of the Chandler wobble is not uniquely identified, it is now recognized that normal climatic processes effectively sustain the wobble against damping (Ponte *et al.*, 1998). In this work we have shown that natural events can exist which sporadically excite the wobble in a very vigorous way. Nowadays, no records remain of the hypothetical paleorotational variations produced by the Black Sea flooding, since no impact on the environment or human life would be produced. However, our results shed light on an unusual aspect of Earth rotation, which profoundly deviates from what we have learned from geodetic observations over the past century (Lambeck, 1980).

Acknowledgements

This paper was written thanks to the encouragement of Andrea Argnani, who first made us notice the possibility of a rapid Black Sea flooding.

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(received March 26, 1999;
accepted June 28, 1999)