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Anomalous Roughness of the Pole Path at the Time of the 1994 Bolivia and Kurile Islands Earthquakes

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Abstract. We report anomalies in the roughness of the path of the pole of rotation at the time of the Bolivia earthquake of June 9, 1994 (M_w = 8.2) and of the Kurile Islands earthquake of October, 4, 1994 (M_w = 8.3). This finding reinforces the results of previous studies, which have indicated changes in the polar motion curvature at the time of major earthquakes.

1. Introduction

The first attempt to correlate the occurrence of large earthquakes with irregularities of the pole path was performed by Mansinha & Smylie (1970). Their least-squares procedure consisted in fitting the polar motion data by consecutive arcs in order to locate the kinks which constitute theoretically the signature of large earthquakes (*e.g.*, Lambeck, 1980). The positive correlation shown by Mansinha and Smylie started a long-standing debate on the 'seismic excitation hypothesis,' which concerns the possibility that the Chandler wobble is maintained by the collective effect of large earthquakes (see Lambeck, 1980 for a review). The main conclusion is that earthquakes are not likely to continuously excite the Chandler wobble, even if sporadically large earthquakes may well serve as a source of excitation. Our purpose here is to suggest a new method to address the problem of 'seeing' the signature of earthquakes in polar motion data, which is based on the notion of surface roughness. In this study, motivated by the availability of high-precision polar motion time-series provided by the International Earth Rotation Service, we show that at the time of the 1994 Bolivia and Kurile Islands earthquakes the roughness of the pole path was subject to a sharp increase, which may possibly represent the trace left on the pole path by the inertia variations due to both the coseismic dislocation and to the possible tectonic motions accompanying these earthquakes.

2. Results

Since the work of Mansinha & Smylie (1970), only few attempts have been made to detect earthquake signals on the pole path by quantitative methods. By a

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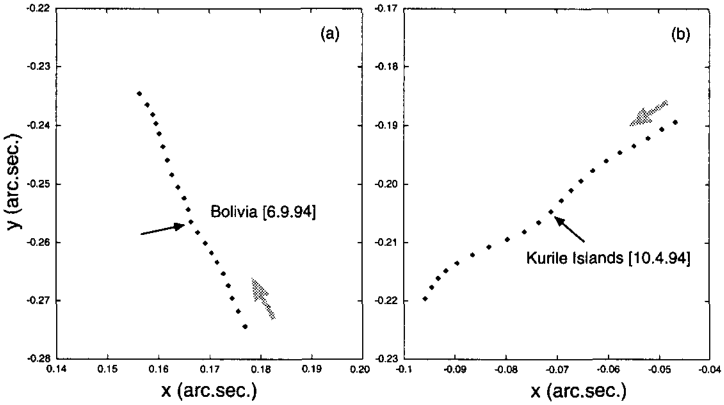

Figure 1. Path of the pole of rotation at 1 day interval at the time of the Bolivia earthquake (a) and of the Kurile Islands earthquake (b). The x and y axes point along the Greenwich meridian and the 90° E meridian, respectively.

deconvolution of the LAGEOS polar motion series, Gross & Chao (1985) have detected a sharp jump of the excitation function at the time of the 1977 Sumba earthquake. Since the observed change could not be explained by the residual deformations due to the earthquake, the current interpretation is that postseismic motions occurring along the subducting slab were the main cause of the excitation (Gross & Chao, 1985; Alfonsi *et al.*, 1997). Another notable example is constituted by the work of Preisig (1992), who showed a strong correlation between the occurrence of large earthquakes and peaks in the amplitude of the atmospheric angular momentum excitation function. He also noticed that many of the large earthquakes occurred between 1984 and 1988 fall in the vicinity of sharp polar motion fluctuations occurring a few days before or after the main shock.

The term 'fluctuation' is used by Preisig (1992) in a quite broad sense, meaning some deviation of the pole of rotation from an ideally regular curve. The reading of the work of Preisig has prompted us to adopt a more quantitative definition, based on the notion of roughness (*e.g.*, Power & Tullis, 1991). In practice, to compute the roughness of the pole path on a certain time interval, we measure the misfit between the real profile of the pole path and an ideal profile. This corresponds to an Euclidean approach to the characterization of roughness of a surface (Power & Tullis, 1991), and closely mimics the definition suggested by Uliana (1997) for applications to rock fractures measurements. We thus compute the quantity

$$R^{(n)} = L/L_0, \tag{1}$$

where L_0 is the distance between the end points of a sequence of n points providing the position of the pole of rotation, and L is the sum of the distances between consecutive points. By its definition, $R^{(n)}$ is always larger than one.

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Distances are measured in the (x,y) plane with x and y located along the Greenwich meridian and the 90° W meridian, respectively.

With the assumption that most of the perturbations in Earth rotation occur within a short time after the earthquake, we decided to compute the roughness over time intervals of a few days. It is thus reasonable to assume that the pole would move along an approximately rectilinear path in the absence of perturbations. A definition of roughness on a longer time-scale would be possible in principle, but in that case the choice of a reference ideal profile for the motion of the pole would be largely arbitrary. The analysis based on the roughness (1) provides different information with with respect to the best-fit procedure employed by Mansinha and Smylie (1970). In fact, the latter method assumes implicitly that the signal due to earthquakes has the shape of a kink in an otherwise perfectly circular path. The roughness (1), on the contrary, should reveal both kinks and other possible fluctuations, such as tectonic movements and aseismic motions which are likely to precede and/or to follow major earthquakes (see Preisig, 1992). Of course, a major drawback is that the roughness, as it is defined here, cannot be used to discern between kinks and other signals possibly associated with non-tectonic processes.

The polar motion data employed here are those given at one-day intervals by the IERS EOPC04 series (*e.g.*, IERS, 1998). In particular, we have focussed our attention on the year 1994, since this year has been characterized by the occurrence of the two largest earthquakes of the last decade from the viewpoint of the potential effects on Earth rotation. They are the Northern Bolivia earthquake of June 9 (M_w = 8.2, depth = 647 km according to the CMT catalog, see *e.g.* Dziewonski *et al.*, 1981) and the Kurile Island earthquake of October 4 (M_w = 8.3, depth = 68.2 km). The Bolivia earthquake has been the deepest earthquake ever recorded (*e.g.*, Kikuchi and Kanamori, 1994). On the basis of the static dislocation theory of Dahlen (1973), the seismic excitation functions for these two earthquakes have moduli of 0.26 and 0.42 milliarcseconds, and arguments of 124.0° and 131.8° E, respectively. Since 1989, no other CMT earthquake had an associated excitation function in excess of 0.2 milliarcseconds. It should be recalled that the excitation functions above are computed for an elastic Earth, and only account for the global residual deformations due to the main shock. They do not include the contribution of phase transitions or melting with associated density variations possibly occurring along the subducting slab, which may be relevant for deep-focus earthquakes such as the Bolivian event (Kanamori *et al.*, 1994).

Figure 1 shows the path of the pole of rotation of the Earth during a time period of 20 days centered on the date of the Bolivia earthquake (panel a) and on that of the Kurile earthquake (b). The gray thick arrows indicate the direction of motion of the pole. The uncertainty on the polar motion data, which are taken from the EOPC04.94 series (*e.g.*, IERS, 1998), are $\sim$ 0.3 milliarcseconds, onoticeably smaller than the symbol employed to draw the paths. It should be kept in mind that this uncertainty is comparable with the amplitude of the excitation function for the two earthquakes as it is predicted by the static dislocation theory (Dahlen, 1973). In both panels of Figure 1 we did not deliberately connect the data points, since this could cause an erroneous interpretation of the data themselves. However, by visual inspection, it is apparent that fluctuations similar to smoothed cusps are visible approximately at the time of the two

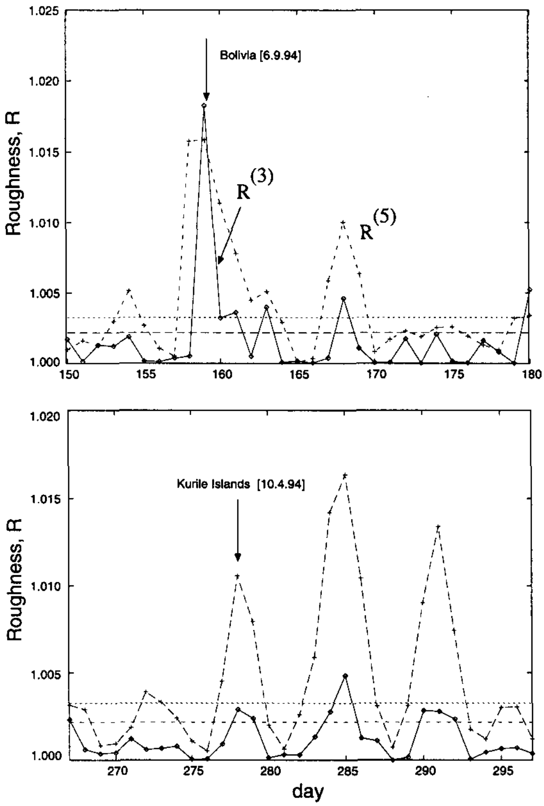

Figure 2. Roughness of the EOPC04.94 series at the time of the Bolivia earthquake (top) and of the Kurile islands earthquake (bottom).

earthquakes. The fluctuation at the time of the Bolivia earthquake appears to be more localized and sharp that the one associated with the Kurile Island earthquake. These qualitative impressions are similar to those reported by Preisig (1992) in his analysis of the polar motion data for the period [1984–1988].

An analysis of the roughness of the polar motion data at the time of the two earthquakes considered here is shown in Figure (2). In both cases, we have considered a time-window of 30 days including the dates of each earthquake; the abscissa shows the days elapsed after December 31, 1993. The roughness R reported in Figure (2) at a given time is computed on a time interval of $n-1$ days centered on that time. We computed the roughness for both $n=3$ (unbroken line) and $n=5$ (dashed) corresponding to time lapses of 2 and 4 days, respectively. A clear anomaly in the roughness is visible across the time t=160 days in the top panel. At this time, which corresponds to the date of the Bolivia earthquake, both $R^{(3)}$ and $R^{(5)}$ are considerably larger than their annual averages, shown in Figure (2) by the lower and upper horizontal lines, respectively. It is interesting to notice that the amplitude of the roughness measured at time $t \sim 160$ days is basically unaffected by the choice of n, being

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$R^{(3)} \simeq R^{(5)}$. This is exactly what one should expect for a sharp, localized cusp, so that this confirms the visual impression obtained by Figure 1. An anomaly in the roughness is also detected close to day 277, when the Kurile Islands earthquake occurred (see bottom frame). This anomaly is best seen in the curve pertaining to $R^{(5)}$, while $R^{(3)}$ does not depart appreciably from its annual average. As for the three subsequent anomalies detected (at days $\sim$ 285 $\sim$ 291, respectively), the signals obtained for n=3 and n=5 have clearly distinct amplitudes. This points to relatively smooth fluctuations, consistent with the visual analysis of Figure (1). Despite the fact that the coseismic excitation function associated with the Kurile Island earthquake was larger (by a factor of $\sim$ 1.6) than the one of the Bolivian earthquake, the roughness found at day 277 is smaller than the one detected at day 160 (see top panel).

3. Conclusions

Using the definition of roughness proposed by Uliana (1997), we have analysed the polar motion time series during 1994, the year of occurrence of the two earthquakes that contributed most to the seismic excitation function in the last decade. Our purpose was to make quantitative the analysis by Preisig (1992) aiming to detect possible signals associated with these earthquakes. The results achieved can be summarized as follows. At the time of the Bolivia earthquake, a sharp anomaly in the roughness can be seen, with an amplitude noticeably larger than its annual average. This anomaly is unique in size during a time-window of 30 days including the date of the earthquake. This signal has the character of a well defined kink or cusp. An anomaly in the roughness is also found at the day of the Kurile Islands earthquake. However, it appears to indicate a smooth fluctuation of the pole, and it is followed by variations of comparable amplitude within a few days. The signal found at the time of the Kurile Island earthquake is smaller than the one pertaining to the Bolivia earthquake, in contrast to the predictions of the static dislocation theory. This latter predicts a seismic excitation function comparable with the uncertainty of the polar motion data at the time of the two earthquakes, whose signal could thus be hardly detected. As a consequence, if the anomalies in the roughness detected at the time of the Bolivia and Kurile earthquakes are indeed real, they may reflect something more than the signal predicted by the static dislocation theory. In particular, in the case of very deep earthquakes such as the Bolivian event, we speculate that the roughness detected may possibly indicate inertia variations induced by transformational faulting (Green & Burnley, 1989) or frictional melting triggering the earthquake (Kanamori *et al.*, 1994), which are not modelled by the classical statical dislocation theory.

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