

## Earth's spin and volcanic eruptions: evidence for mutual cause-and-effect interactions?

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### ABSTRACT

The angular velocity of Earth's rotation shows decadal oscillations due to the lunisolar gravitational torque, as well as inter- or intra-annual changes arising from the angular momentum exchange between the atmosphere and the solid Earth. The energies involved in the Length of Day (LOD) variations may affect the crustal deformation rate and seismic energy release on a global scale. We found significant correlation between the occurrences of major volcanic eruptions and the LOD pattern since AD 1750. On a multiyear scale, eruption frequency worldwide increases with LOD changes. Moreover, the injection of sulphur gases into the atmosphere

during major eruptions is accompanied by significant inter-annual LOD variations. This provides evidence of complex mutual cause-and-effect interactions: stress changes induced by multiyear variations in Earth's spin may affect climactic volcanic activity; also, the atmosphere's dynamic response to volcanic plumes may result in global changes of wind circulation and climate, with consequent LOD variations.

Terra Nova, 26, 78–84, 2014

### Introduction

The angular velocity of Earth's rotation is influenced by periodical processes on different time-scales. Tidal dissipation due to the gravitational torque exerted by the Moon and Sun reduces, while the decrease in Earth's oblateness increases the Earth's angular velocity; these combine to give rise to long-term (decadal to secular) LOD oscillations (Lambeck, 1980). Fortnightly, monthly, semi-annual and annual zonal tides produce short-term LOD fluctuations with amplitudes of ~1 ms (Jault *et al.*, 1988; Kane and Trivedi, 1990). Moreover, subdecadal LOD changes arise from the angular momentum exchange between the atmosphere, oceans and solid Earth (Barnes *et al.*, 1983; Marcus *et al.*, 1998). The energies involved in LOD variations may affect the crustal deformation rate and seismic energy release on a global scale (Anderson, 1974; Wang *et al.*, 2000). As even small perturbations of the Earth's angular velocity can release substantial amounts of gravitational energy (Press and Briggs, 1975), the decadal LOD varia-

tions have been regarded as a possible modulator of the time-space distribution of large earthquakes (Anderson, 1974; Varga *et al.*, 2005) and as a driving factor for mass redistribution on a plate tectonic scale (Wang *et al.*, 2000; Riguzzi *et al.*, 2010). From the energy budget of the Earth-Moon system, the amount of power released by Earth's rotation variations can be estimated at  $1.2 \times 10^{20} \text{ J a}^{-1}$  (Riguzzi *et al.*, 2010). Considering the aliquot of power dissipated in the Earth's mantle ( $0.42 \times 10^{19} \text{ J a}^{-1}$ ) and hydrosphere ( $0.75 \times 10^{20} \text{ J a}^{-1}$ ), a residual power of  $\sim 0.4 \times 10^{20} \text{ J a}^{-1}$  in the Earth's system (Riguzzi *et al.*, 2010) can be released in different forms, including seismicity (Anderson, 1974; Riguzzi *et al.*, 2010) and the generation of lithosphere-mantle relative shear on a global tectonic scale (Knopoff and Leeds, 1972; Wang *et al.*, 2000; Riguzzi *et al.*, 2010).

Here, we consider the possible effects of LOD fluctuations on volcanic activity. Conversely, we also consider the possible effects of volcanism on LOD. Indeed, short-period LOD variations have been attributed to atmospheric perturbations (Barnes *et al.*, 1983). Also, Dickey *et al.* (2011) document a relationship between decadal LOD variations and global surface temperature variations since 1850. Climactic volcanic activity releases considerable amounts of

pyroclasts and gases into the stratosphere, which alter the Earth's radiation balance, with effects on surface temperatures, global atmospheric circulation and climate (Robock, 2000). Volcanism is regarded as the first factor in climate changes in the 1600–1850 period (Free and Robock, 1999). In the last 250 years, major eruptions have produced episodes of global or hemispheric cooling over 2–3 years (Robock and Mao, 1995). The most important effects on climate are due to sulphur emission (Devine *et al.*, 1984; Free and Robock, 1999): sulphate aerosols injected into the stratosphere may circle the globe in a few weeks (Robock and Matson, 1983; Bluth *et al.*, 1992) and backscatter to space a fraction of the solar radiation. The effects on climate strongly depend on the eruption latitude and wind patterns (Bourassa *et al.*, 2012). The volcano-climate system may also experience the inverse response, i.e., climate fluctuations on the 10–100 year time scale may lead to crustal stress changes by loading and unloading of ice and water masses and by Earth's axis and spin changes, which may augment seismic and volcanic potential (Ramphino *et al.*, 1979).

### Observational data

To detect possible correlations between major eruptive activity and

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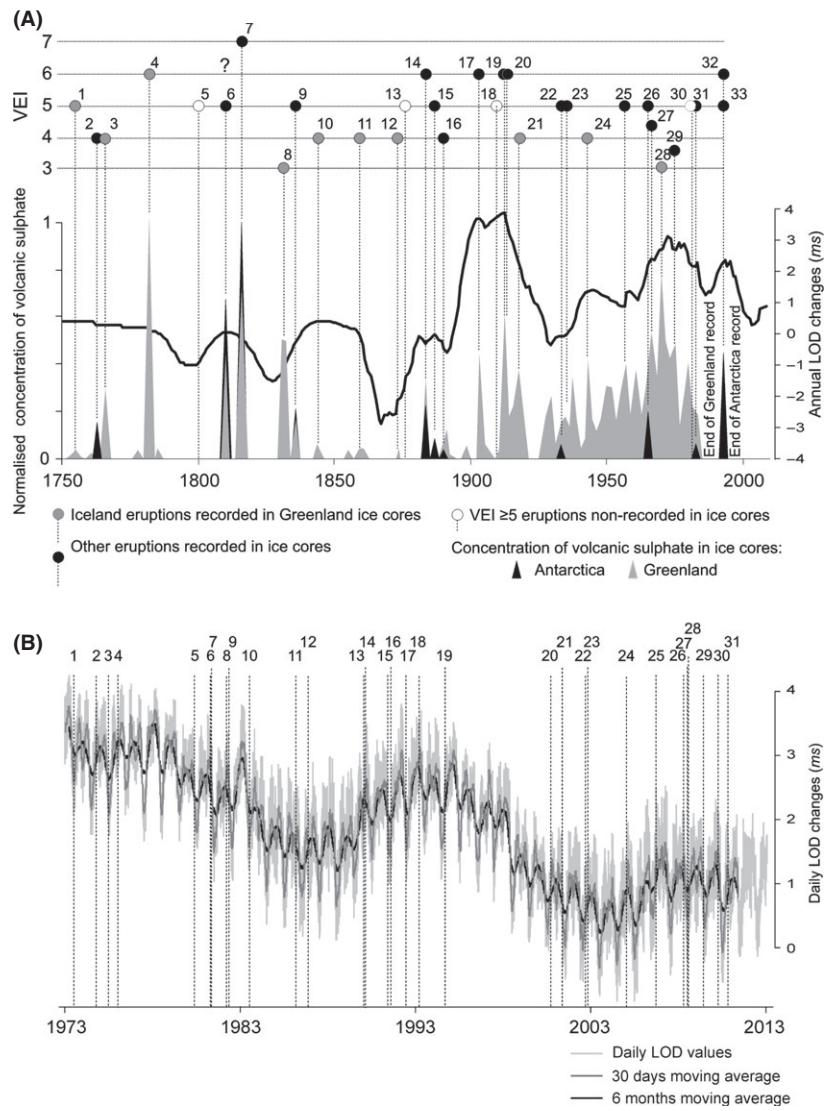
LOD oscillations in the last few centuries, we analyse the datasets available from: (i) the International Earth Rotation and Reference System Service (IERS-EOP) LOD database (International Earth Rotation and Reference System Service (IERS), Earth Orientation Center at the Paris Observatory (<http://hpiers.obspm.fr/eop-pc/>)); (ii) the time-space distribution of major volcanic eruptions since AD 1750, including 143 events with Volcanic Explosivity Index (VEI)  $\geq 4$  in different geodynamic settings (from the Smithsonian Institution catalogue, available online at: [www.volcano.si.edu/world/](http://www.volcano.si.edu/world/); Siebert and Simkin, 2002; Palladino and Sottili, 2012). Volcanic eruptions rate  $VEI \geq 4$  when at least  $0.1 \text{ km}^3$  of tephra is erupted, and column height exceeds 10 km; the chosen eruption threshold should avoid reporting bias (e.g. Deligne *et al.*, 2010); (iii) the records of volcanic sulphur output from Greenland and Antarctica ice-core data (Zielinski *et al.*, 1994; Cole-Dai *et al.*, 1997) (Fig. 1).

On a secular time-scale, decadal LOD oscillations since A.D. 1750 show a rough parallelism with the temporal pattern of volcanic sulphate concentration in ice cores (Fig. 1A). Although the recorded sulphate peaks are affected by volcano location to variable extents (e.g. over-recording of Icelandic SO<sub>2</sub>-rich eruptions in Greenland ice cores), most peaks are correlated with major explosive eruptions worldwide. These often occur concomitant to sharp changes (either peaks or points of inflection) in the LOD trend. The coincidence with LOD peaks mostly holds for the most powerful eruptions (VEI  $>5$ ) even without detectable sulphur records in ice cores (Fig. 1A). The occurrence of  $VEI \geq 4$  events vs. LOD pattern is evaluated quantitatively in the Statistical analysis section (see also Fig. 2).

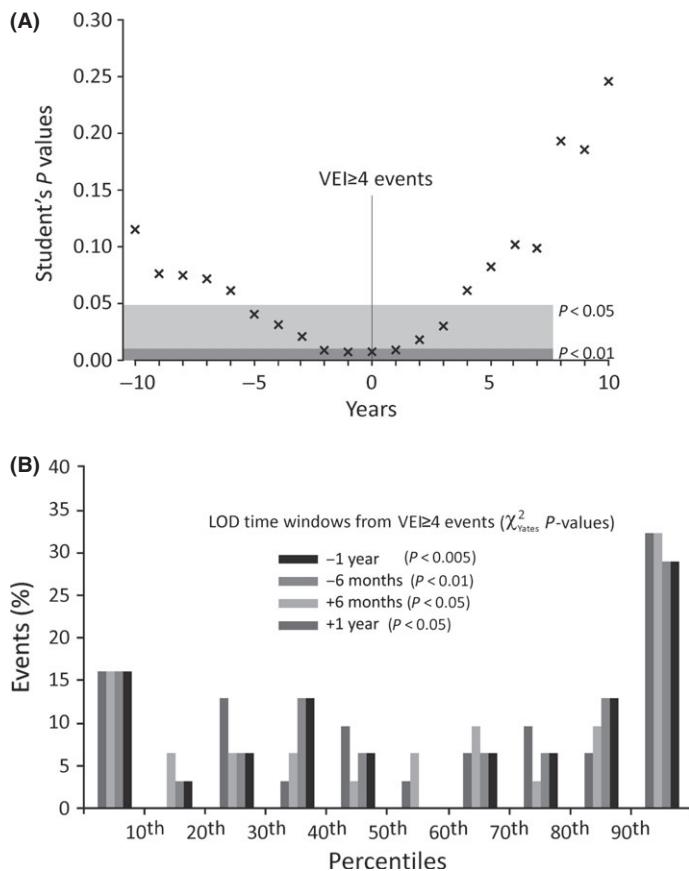
The LOD pattern typically shows the superposition of multiyear oscillations, due to solar forcing and/or core-mantle coupling inside the Earth (Mound and Buffett, 2003), and intra-annual oscillations due to atmospheric circulation in response to seasonal thermal changes (Le Mouël *et al.*, 2010). In particular, in the years following two major explosive eruptions responsible for major

atmospheric perturbations (Robock, 2000), i.e. El Chichón 1982 (Mexico; VEI5) and Pinatubo 1991 (Philippines; VEI6), it can be noted that the intra-annual LOD oscillations wane and pronounced single peaks in the absolute LOD values appear (Fig. 3A, B). The effect of El Chichón on LOD pattern seems more pronounced, but limited to

1 year after the eruption, while the effect of Pinatubo is less pronounced, but extended to at least 2 years, parallel to the intensity and duration of the apparent transmission anomalies due to volcanic SO<sub>2</sub> release into the atmosphere (Fig. 3A, B). Although Zhou *et al.* (2001) refer the 1983 LOD peak to the El Niño Southern Oscillation (ENSO) 1982–83 event,



**Figure 1** (A) Volcanic sulphate concentrations from Greenland and Antarctica ice-core records (Zielinski *et al.*, 1994; Cole-Dai *et al.*, 1997), compared with the annual LOD variations since AD 1750. Numbers refer to the 33 corresponding eruption occurrences (see Table S1), which include all major eruptions with  $VEI \geq 5$  (15% of the 143  $VEI \geq 4$  events), as well as minor events with a recognized sulphate record. (B) Occurrence of volcanic eruptions with  $VEI \geq 4$  (see details in Table S4) compared with the daily LOD changes since 1973. Of note, LOD cycles show intra-annual maxima and minima, as evidenced by the fluctuations of daily LOD values around the 30-day and 6-month moving averages. The increasing occurrence of  $VEI \geq 4$  events correlated with LOD peaks is evaluated statistically in the text and in Fig. 2B.



**Figure 2** (A) Statistical significance of annual LOD perturbations measured  $\pm 10$  years around the occurrence of VEI $\geq 4$  eruptions since AD 1830. The average annual LOD changes measured from 2 years prior to 1 year after the occurrence of VEI $\geq 4$  eruptions deviate significantly (Student's probability,  $P < 0.01$ ) from annual LOD changes averaged since AD 1830. The  $-5$ -year to  $+3$ -year interval also displays significant deviations (Student's probability,  $P < 0.05$ ) from the average annual LOD changes. (B) Distribution of VEI $\geq 4$  eruptions (% of 31 events since 1973) vs. intra-annual LOD oscillations (percentiles). By considering the differences between the daily LOD changes and the 6-months and 1-year moving averages (from Fig. 1B), we define minima and maxima LOD peaks as values lower and higher than the 10th and 90th percentiles respectively. The plot shows that nearly half of the VEI $\geq 4$  events cluster around LOD peaks calculated for intervals of  $\pm 6$  months and  $\pm 1$  year from large eruptions. In particular, nearly 30% of VEI $\geq 4$  eruptions occur concomitant to positive LOD peaks (i.e. Earth's spin deceleration). Probability values ( $P$ ) derived from chi-square test with the Yates' correction (see text) rule out that the observed distribution may derive from a random sampling.

Fig. 3B suggests that the ENSO 1986–87 occurrence did not influence the intra-annual LOD trend.

On these grounds, we hypothesize mutual cause-and-effect relationships between LOD variations and the occurrence of major explosive eruptions.

#### Statistical analysis

We test statistically the hypothesis that the occurrence of large explosive

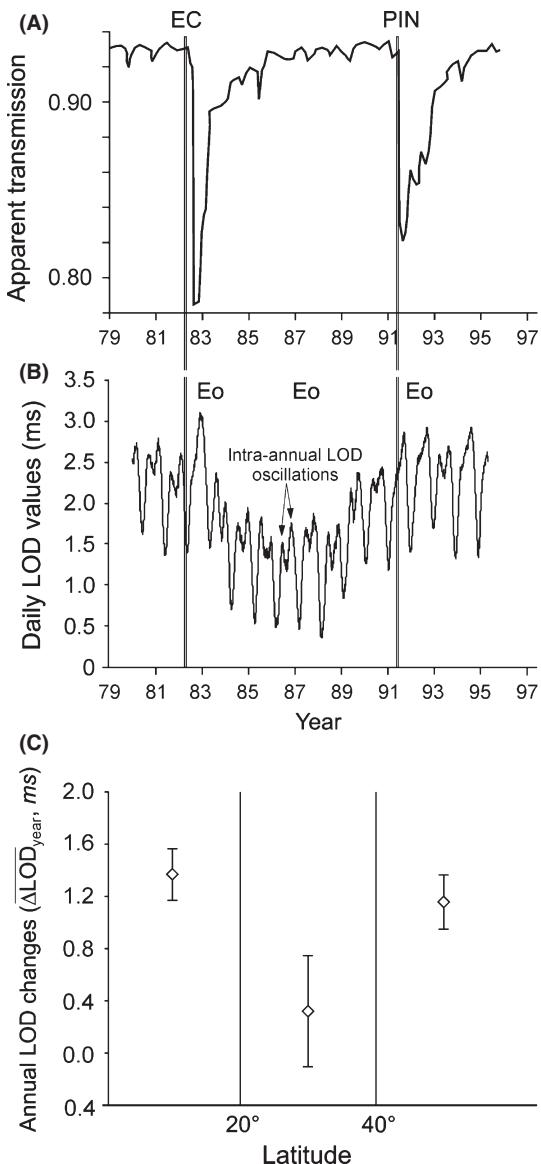
eruptions is significantly distinguishable from a time-stationary Poisson process (i.e. lack of eruption clustering, modulation or trend with time) and is instead correlated with LOD changes at different time-scales. For each time interval considered, we calculate  $\overline{\Delta LOD}_{\text{yrs}}$  as the algebraic sum of the annual deviations of the day length from the SI day (available from the LOD time series database), divided by the duration of the interval (see Table S2).

First, from the LOD time series in the period since AD 1830 (for which the LOD database is more reliable), we consider the annual values averaged over the 107 years with no VEI $\geq 4$  eruption occurrences ( $\overline{\Delta LOD}_{\text{yrs}} = 0.63$  ms) vs. the 76 years with one or more VEI $\geq 4$  eruptions ( $\overline{\Delta LOD}_{\text{yrs}} = 1.26$  ms). The statistical significance of the LOD difference between years with at least one vs. years without VEI $\geq 4$  eruptions is evaluated through the probability  $P$  determined by the Student's test, which also takes into account sample sizes and population standard deviations. The obtained  $P < 0.04$  indicates an insignificant probability that the observed difference may arise from a random sampling of a single, normally distributed population of data.

To evaluate the degree of correlation of LOD changes with occurrences of large eruptions through time, and thus to assess possible mutual cause-and-effect relationships, we also consider  $\overline{\Delta LOD}_{\text{yrs}}$  changes around years with one or more VEI $\geq 4$  eruptions. Specifically, we apply the Student's test to evaluate the probabilities that  $\overline{\Delta LOD}_{\text{yrs}}$  changes in the periods, respectively, preceding and succeeding the years of VEI $\geq 4$  eruption occurrences are randomly distributed. Figure 2A shows that the lowest probabilities of random  $\overline{\Delta LOD}_{\text{yrs}}$  changes ( $P < 0.01$ ) are obtained between 2 years before and 1 year after eruptions. Moreover,  $P < 0.05$  values indicate that 5–3 years before and 2–3 years after years of VEI $\geq 4$  eruptions  $\overline{\Delta LOD}_{\text{yrs}}$  is still distinguishable from (i.e. significantly higher than) other periods.

Now, we test the consistency of the LOD-VEI $\geq 4$  relationship by analysing the variability of the average annual rate of occurrence of VEI $\geq 4$  events since AD 1830. We notice the occurrence of 0.76 events per year for annual LOD changes above the 75th percentile, and of 0.42 events per year for annual LOD changes below the 25th percentile (see Table S3). The increasing number of events per year (by ~79%;  $P = 0.03$ ) again indicates that the rate of occurrence of large eruptions is positively correlated with annual LOD changes.

Let us now focus on an independent dataset listing the daily LOD



**Figure 3** (A) Effects of volcanic SO<sub>2</sub> injection into the stratosphere, as revealed by sharp decreases in the apparent transmission of the atmosphere following the El Chichón 1982 (EC) and Pinatubo 1991 (PIN) eruptions (after Robock, 2000). (B) Daily LOD variations (smoothed by running averages of 30-days) during 1979–95. Of note, in the year following both EC and PIN eruptions, LOD seasonal oscillations fade away, and LOD values define single annual peaks with an increase in the order of 0.5 ms. The PIN eruption seems to affect the LOD pattern for at least 2 years. The occurrences of El Niño (Eo) are also reported for comparison. (C) Annual LOD variations ( $\Delta LOD_{yrs}$ ; see text for explanation) following VEI  $\geq 4$  eruptions, grouped in three latitude intervals, since AD 1830. The year following eruptions either at low ( $<20^\circ$ ; 49 events) or middle-high ( $>40^\circ$ ; 41 events) latitudes is affected by significantly higher LOD changes (see text for details on Student's test) than the year following eruptions at intermediate latitudes ( $20^\circ$ – $40^\circ$ ; 10 events). Error bar is  $\pm 1$  standard error of the mean.

changes (i.e. the daily deviation from the SI duration of the day; also available from the IERS LOD data source) since 1973. The eruption catalogue reports 31 VEI  $\geq 4$  events with

a reliable date of occurrence in the last 40 years (Table S4). The differences between the 6-month moving averages and daily LOD changes show positive and negative fluctua-

tions of  $\pm 1.5$  ms, corresponding to maxima and minima, respectively, of intra-annual LOD cycles (Fig. 1b). We find that  $\sim 50\%$  of VEI  $\geq 4$  eruptions occurred concomitant to extreme daily LOD fluctuations (i.e. below the 10th and above the 90th percentiles; Fig. 2b), i.e. with at least 2.5 times higher probability of occurrence.

To evaluate statistically the increasing occurrence of VEI  $\geq 4$  events concomitant to peaks of intra-annual LOD cycles, as evidenced by the above VEI  $\geq 4$  vs. LOD frequency distribution, we apply the chi-square test with the Yates' correction (Yates, 1934) to prevent overestimation of statistical significance for small datasets:

$$\chi^2_{Yates} = \sum_{i=1}^N \frac{(|O_i - E_i| - 0.5)^2}{E_i} \quad (1)$$

where  $O_i$  is the observed frequency,  $E_i$  is the expected (theoretical) frequency, asserted by the null hypothesis, and  $N$  is the number of events. In our case, the null hypothesis is that the 31 events are randomly distributed with respect to daily LOD changes. Specifically, we consider the eruption occurrences within intervals of 10th percentiles of the differences between the 6-month moving averages and daily LOD changes. The chi-square test rejects a random distribution of VEI  $\geq 4$  events with a  $>99.5\%$  confidence (Fig. 2b) and instead points out that the highest probability of a VEI  $\geq 4$  event occurring is during extreme LOD fluctuations (i.e. below the 10th or above the 90th percentile).

Thus, statistical evidence supports a possible LOD tuning of major explosive eruptions. Next, we consider the possible effects of large explosive activity on the LOD pattern, via induced climate perturbations. Overall, if we analyse  $\Delta LOD_{yrs}$  measured 1 year after each VEI  $\geq 4$  eruption since AD 1830 (Fig. 3C), it appears that LOD perturbations are higher following eruptions at low ( $<20^\circ$ ;  $\Delta LOD_{yrs} = 1.38$  ms) and middle-high ( $>40^\circ$ ;  $\Delta LOD_{yrs} = 1.17$  ms) latitudes than following eruptions at intermediate latitudes ( $20^\circ$ – $40^\circ$ ;  $\Delta LOD_{yrs} = 0.35$  ms). The probability,  $P$ , that the observed  $\Delta LOD_{yrs}$  distribution within the three VEI  $\geq 4$

latitude groups may derive from a random sampling of LOD values (null hypothesis) is evaluated through the Student's test. Following large eruptions at middle latitudes,  $\Delta LOD_{\text{yrs}}$  is significantly higher than at low latitudes ( $P < 0.05$ ) and – to a lesser degree – than at middle-high latitudes ( $P < 0.09$ ). Also,  $\Delta LOD_{\text{yrs}}$  following eruptions at low latitudes is significantly ( $P < 0.05$ ) higher than  $\Delta LOD_{\text{yrs}} = 0.89$  ms averaged over the whole time series since AD 1830.

To avoid the effects of outliers and better constrain the significance of the above latitude dependence, we also analysed the percentile distribution of  $\Delta LOD_{\text{yrs}}$  following VEI  $\geq 4$  events at different latitudes. We found that following intermediate-latitude eruptions, 33.3% of the recorded  $\Delta LOD_{\text{yrs}}$  values are below the 10th percentile, in comparison to 6.1% and 6.3%, respectively, following eruptions at low and middle-high latitudes. In addition, 38.8% and 39.0% of the  $\Delta LOD_{\text{yrs}}$  values following eruptions at low and middle-high latitudes, respectively, are allocated in the 4th quartile, in comparison to 22.2% after intermediate-latitude eruptions. These findings show that LOD values increase significantly (i.e. Earth's spin decelerates) following eruptions at low and middle-high latitudes.

#### LOD tuning of major explosive eruptions?

Previous studies proposed that LOD variations may increase the rate of occurrence of large earthquakes (Anderson, 1974; Riguzzi *et al.*, 2010). The sensitivity of eruption occurrences to small crustal stresses on local (e.g. Sottili *et al.*, 2007; Sottili and Palladino, 2012) to global scales (Jupp *et al.*, 2004; Mason *et al.*, 2004; Watt *et al.*, 2013) may explain the link between LOD changes and volcanic eruptions. On these grounds, we suggest that the power released by Earth's rotation changes may also appreciably affect the rate of eruption occurrences.

Here, we found a statistically significant relationship supporting a possible LOD influence on the occurrence of major explosive eruptions worldwide. Specifically, based on the time lapse of the statistically signifi-

cant dependence defined by the  $P < 0.05$  threshold (8 years, Fig. 2a), we consider the AD 1830 to present LOD changes as the sum of yearly LOD values within 5-year time windows, and the number of VEI  $\geq 4$  events occurring within the following 3 years. We find a positive correlation between LOD changes and VEI  $\geq 4$  eruption rate: For a LOD increase from 3.3 to 11.3 ms through 5 years, the frequency of VEI  $\geq 4$  eruptions during the following 3 years increases from 0 to 0.6 events per year (i.e. 5 events/3 years) (Fig. 4). The degree of correlation is estimated through the Pearson product-moment correlation coefficient,  $r$ , which yields a value of 0.97 (Fig. 4). In addition, the obtained relationship of LOD changes through 5 years vs. VEI  $\geq 4$  rate through 3 years was tested by comparison with a randomized VEI  $\geq 4$  catalogue. In particular, to eliminate any possible *a priori* causal relationships, we reshuffled the catalogue data repeatedly like a deck of cards, by reassigning a random year of occurrence between 1830 and the present to each eruption and obtaining 100 lists of randomized eruption sequences. Unlike the historical dataset, the randomized time series show no significant

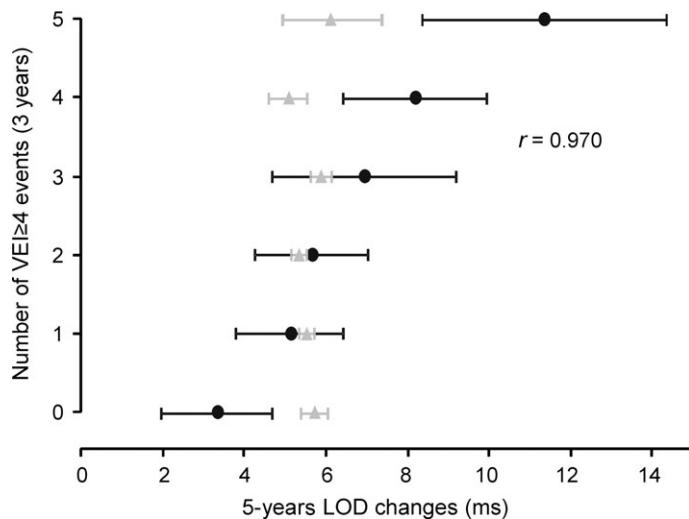
dependence of VEI  $\geq 4$  occurrences on LOD changes (Fig. 4).

We observe that the 5-year LOD oscillation period is much longer than that related to the angular momentum exchange between the atmosphere and the solid Earth (in the order of weeks to months; Barnes *et al.*, 1983) and, instead, is attributed to the angular momentum exchange between Earth's mantle and core (Mound and Buffett, 2003).

#### Volcanic tuning of LOD?

Statistical analysis also provides evidence for the effects of large explosive activity on the LOD pattern. Specifically, we found that both yearly and daily LOD values are significantly affected by VEI  $\geq 4$  events for periods of at least up to 3 years (Fig. 2). Moreover, VEI  $\geq 4$  eruptions at low and middle-high latitudes induce relatively higher LOD perturbations (Fig. 3). Although a previous study (Anderson, 1974) hypothesized that explosive eruptions may be the ultimate cause of the significant LOD change at the turn of the 19th–20th century, this subject has not been further addressed in the literature.

As the redistribution of westerly vs. easterly wind intensities is the



**Figure 4** Relationship of VEI  $\geq 4$  eruption frequency vs. LOD variations since AD 1830. The Pearson product-moment correlation coefficient ( $r = 0.97$ ) indicates a high degree of correlation between LOD variations within 5-year time-windows and the number of VEI  $\geq 4$  events during the following 3 years (black circles). The selected time span derives from the Student's  $P < 0.05$  threshold in Fig. 2a. Vertical bars are the standard deviation of the mean. Randomized data of eruption occurrences (grey triangles) are also plotted for comparison (see text for explanation).

main mechanism for angular momentum exchange between the atmosphere and the solid Earth (e.g. Barnes *et al.*, 1983; Neef and Matthes, 2012), responsible for Earth's spin changes, we infer that a major eruption may induce significant LOD perturbations through the radiative and chemical effects of injected sulphur gases on the global atmospheric circulation.

Our findings are consistent with the general view that eruptions at low and high latitudes have a greater impact on climate (Robock, 2000; Oman *et al.*, 2006; Robock *et al.*, 2007) and, specifically, with the General Circulation Models in the Northern hemisphere, according to which high-latitude ( $>50^\circ\text{N}$ ) eruptions may even weaken the monsoon by reducing the incoming shortwave radiation (Graf, 1992). Also, the influence of high-latitude  $\text{VEI} \geq 4$  eruptions on LOD is partly attributable to the sulphur-rich nature of Icelandic volcanism. For instance, the  $\text{VEI}_4$ , 1783–85 Laki eruption produced 1.7 times more  $\text{SO}_2$  than the  $\text{VEI}_7$ , 1815 Tambora eruption, with substantial climate effects (Oman *et al.*, 2006).

In addition, large volcanic eruptions have a significant impact on regional to global precipitation patterns (Trenberth and Dai, 2007; Timmreck, 2012; Iles *et al.*, 2013). The related changes in continental water storage may thus represent a further component in the LOD variations (Chao and O'Connor, 1988; Chao, 1989; Yan and Chao, 2012).

## Concluding remarks

We found evidence for the mutual forcing of Earth's spin and volcanic activity on different time-scales. Annual to multi-annual LOD fluctuations induced by astronomical factors and Earth's internal dynamics may result in crustal stress variations and affect the time-space distribution of major volcanic eruptions worldwide. In their turn, major volcanic eruptions at different latitudes, which have different impacts on wind circulation (Robock and Matson, 1983; Graf, 1992; Oman *et al.*, 2006), may affect LOD pattern to variable extents in the succeeding few years. This implies that LOD changes also

reflect volcanically induced climate changes, consistent with the observed relationship between decadal LOD changes and global surface temperature variations since 1850 (Dickey *et al.*, 2011). On these grounds, the LOD response to volcanic forcing may provide a baseline to evaluate the increasing anthropogenic vs. natural impact on climate changes over the last centuries.

Finally, the latitude distribution of the 143  $\text{VEI} \geq 4$  eruptions worldwide since AD 1750 (see Fig. S1) shows an asymmetry similar to that of  $M_w \geq 7.0$  earthquakes (Riguzzi *et al.*, 2010). Specifically, previous studies related the variations in the seismicity rate during the 1900–2007 time span to gravitational triggers, i.e. the number of  $M_w \geq 7.0$  earthquakes increases with increasing LOD (Riguzzi *et al.*, 2010). This suggests a common LOD tuning of geodynamic activity, including seismic and volcanic activities, as well as plate tectonic dynamics (Knopoff and Leeds, 1972; Wang *et al.*, 2000; Varga *et al.*, 2005; Riguzzi *et al.*, 2010).

## Acknowledgements

We thank P. Varga and D.M. Pyle for meaningful reviews of the manuscript.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Fig. S1.** Right: Temporal distribution of eruption latitudes for the 143 VEI  $\geq 4$  events since AD 1750 to present (from the Smithsonian Institution catalogue, available online at: [www.volcano.si.edu/world/](http://www.volcano.si.edu/world/); Siebert and Simkin, 2002), compared with decadal LOD oscillations. Vertical bars are the standard deviations from the mean. Left: The latitude distribution of VEI  $\geq 4$  eruptions worldwide (grouped in 10° latitude bins) shows a similar pattern to that of  $M_w \geq 7.0$  earthquakes (earthquake data from Riguzzi *et al.*, 2010).

**Table S1.** List of the eruptions reported in Figure 1a, including VEI  $\geq 5$  events (from the Smithsonian Institution catalogue, available online at: [www.volcano.si.edu/world/](http://www.volcano.si.edu/world/); Siebert and Simkin, 2002), and minor events with recognized sulphate record from Greenland and Antarctica ice cores (Zielinski *et al.*, 1994; Cole-Dai *et al.*, 1997) since AD 1750 to present.

**Table S2.** Input parameters for evaluating the statistical significance of yearly LOD changes (expressed by  $\Delta LOD_{\text{yrs}}$  in the text) vs. occurrences of VEI  $\geq 4$  eruptions since AD 1830 to present. For each time interval considered,  $\Delta LOD_{\text{yrs}}$  is calculated from the algebraic sum of the annual deviations of the day length from the SI day (available from the LOD time series database), divided by the duration of the interval.

**Table S3.** Variability of the average annual rate of occurrence of VEI  $\geq 4$  events since AD 1830 to present vs. yearly LOD changes ( $\Delta LOD_{\text{yrs}}$ ) expressed as percentiles.

**Table S4.** List of VEI  $\geq 4$  eruptions since 1973 reported in Figure 1b (from the Smithsonian Institution catalogue; available online at: [www.volcano.si.edu/world/](http://www.volcano.si.edu/world/); Siebert and Simkin, 2002).

Received 5 February 2013; revised version accepted 12 September 2013