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Contribution of coseismic deformations on the current expansion of the Earth

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ABSTRACT

In this paper, the effects of earthquake source parameters (especially the rake angle and the dip angle) on changes in the overall volume and mean radius of the Earth are discussed, and it is herein concluded that dip-slip earthquakes produce the maximum changes in the Earth's mean radius. We computed almost 40 years of changes in the Earth's mean radius induced by approximately 41,064 events (M*w* ≥ 4.0) from 1976 to 2014 and estimated the change rates of the Earth's mean radius from 1976 to 2014 and 1994–2014, which were 0.02 mm/yr and 0.06 mm/yr, respectively. It is worth noting that the expansion of the Earth's mean radius is dominated by thrust-type earthquakes, and earthquakes in the northern hemisphere have caused the Earth to expand faster. Compared to the expansion rate evaluated using geodetic data, the expansion rate caused by earthquakes can account for approximately 10–30% of the current expansion rate, which may demonstrate that earthquakes can be considered to be additional physical processes that are responsible for the current expansion of the Earth. We also discuss the expansion rate induced by plate motions on geological time scales, which is similar to the expansion rate derived using geodetic data.

1. Introduction

Earthquakes generate changes in the Earth's overall volume by producing permanent deformations in the Earth's interior and surface that lead to other geophysical processes. Han et al. (2006) retrieved the signature of gravity changes due to the crustal dilatation (crust volumetric increase) induced by the 2004 Sumatra earthquake (M*w* 9.3) from space geodetic gravity data. Ogawa and Heki (2007) discussed the diffusion of the supercritical water in the deep mantle due to the volume changes on the geoid depression induced by the 2004 Sumatra earthquake (M*w* 9.3). Cambiotti et al. (2011) derived the localized volume change induced by earthquakes on dip-slip faults based on the summation of the normal modes and generally discussed the volume changes due to large earthquakes such as the 2004 Sumatra earthquake (M*w* 9.3). Xu and Sun (2014) proposed a method of computing earthquake-induced changes in the Earth's overall volume based on elastic spherical-Earth dislocation theory (Sun and Okubo, 1993; Sun et al., 2009) and generally discussed the changes in the Earth's overall volume through the expression and a case study. They concluded that earthquakes along thrust faults cause the Earth to expand and earthquakes along normal faults cause the Earth to contract. Earthquakes with moment magnitudes greater than 7.0 that occurred from 1980 to 2014 have been tested as reasonable candidate excitation sources that can cause the Earth to expand (Xu and Sun, 2014), and it has been demonstrated that earthquakes have only slightly changed the Earth's overall volume and caused the Earth to expand at a rate of 0.01 mm/yr. However, the contributions of earthquakes of different types, smaller magnitudes (<M*w* 7.0) and different locations have not been discussed.

The relative motions among the plates can shrink or accrete the total area of each plate on geological time scales. If the changes in the areas of the plates are only attributed to the changes in the Earth's overall volume, the former can also correspond to the changes in the Earth's mean radius. Under the assumptions that the Earth is a perfect sphere and the plates are completely rigid, Cao et al. (2009) concluded that the current expansion rate of the Earth's mean radius ranges from 0.16 to 0.25 mm/yr by analyzing the variations in the Earth's surface area based on the NUVEL-1 plate motion model (Demets et al., 1990). However, they did not consider the plate motion models published by Bird (2003), which added 38 micro plates that include more deformations at the plate boundaries. Earthquakes are a consequence of the underlying processes

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of plate tectonics, but we still do not know the relation between the expansions caused by earthquakes and those caused by plate tectonics.

The asymmetry in the expansion rates in the northern hemisphere and the southern hemisphere is another interesting phenomenon. Jin and Zhu (2003) analyzed 20 years of space geodetic data and concluded that the southern hemisphere is expanding at a decelerating rate. Cao et al. (2009) concluded that the southern hemisphere is expanding, whereas the northern hemisphere is contracting.

In the present work, we studied the features of how the rake and dip angles affect earthquake-induced overall volume change in the Earth. The cumulative changes and the change rate of the Earth's mean radius caused by earthquakes were computed for the time period from 1976 to 2014. The impacts of earthquakes of different magnitudes and types on the changes in the Earth's mean radius are discussed. The effects of earthquakes in the northern and southern hemispheres on the changes in the Earth's mean radius were studied. We also discuss the expansion rate based on plate motion models on geological time scales.

2. Theoretical principle

To evaluate changes in the Earth's overall volume induced by coseismic deformations, Xu and Sun (2014) proposed a method based on elastic dislocation theory (Sun and Okubo, 1993; Sun et al., 2009). The computation was performed with a spherical, elastic and layered earth using a preliminary reference Earth model (PREM) (Dziewonski and Anderson, 1981). The analytical expressions for the coseismic volume changes for three types of dislocation sources were derived in Xu and Sun (2014). Taking earthquakes as the shear sources, we can rewrite the volume change expression as

$$\Delta V = 2\pi \left(h_0^{33} - h_0^{22}\right) \sin\lambda \sin 2\delta \times UdS \quad (01)$$

where h_0^{33} and h_0^{22} are the dislocation Love numbers defined by Sun et al. (2009), λ and δ are the rake angle and the dip angle of the seismogenic fault, respectively, and U and dS are the mean slip and the area of the seismogenic fault, respectively. Neglecting the high-order small quantities, we can evaluate the coseismic change in the Earth's mean radius using the following expression:

$$\Delta R = \frac{\Delta V}{3V} R \quad (02)$$

where R is the Earth's mean radius, and V is the Earth's entire volume.

We show how the rake and dip angles act on the volume change in the Earth in this section (Fig. 1).

When the range of the rake angle is -180° to 0°, the changes in the Earth's overall volume are negative, which means that earthquakes along a normal fault contract the Earth; on the contrary, the changes in the Earth's overall volume are positive, which demonstrates that earthquakes along thrust faults expand the Earth. For a given rake angle, the change in the Earth's overall volume is symmetric with a dip angle of 45°. The results show that dip-slip (λ=90°, δ=45°) earthquakes apparently produce the maximum changes in the Earth's overall volume. The earthquakes along strike-slip faults do not theoretically produce changes in the Earth's overall volume.

3. Cumulative coseismic changes in the earth's mean radius

Here, we compute almost 40 years (from 1976 to 2014) of changes in the Earth's mean radius induced by successive earthquakes using a catalog whose seismic source parameters are provided by the global centroid moment tensor (GCMT) project (Dziewonski et al., 1981; Ekström et al., 2012). The GCMT catalog provides a list of worldwide earthquakes and contains approximately 41,064 events from 1976 to 2014 with magnitudes greater than 4, although the list is probably complete only for magnitudes greater than 5.0, epicenter locations, and CMT solutions (Fig. 2).

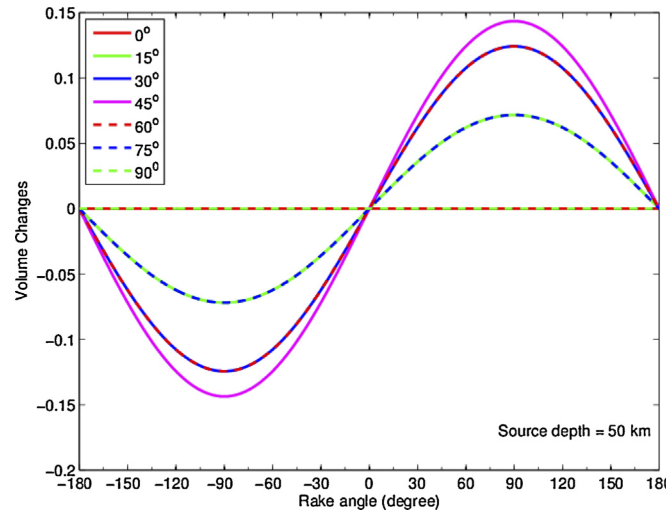

Fig. 1. The changes in the Earth's overall volume due to a point source ($UdS/R^3 = 1$) with variable rake angles and dip angles; the source depth was set to 50 km.

However, the GCMT catalog does not provide all the necessary information needed to apply our approach. The length, width and mean slip of the fault plane need to be known in addition to the magnitude of the earthquake. We adopted a source scaling law determined using earthquake magnitudes or seismic moments to obtain the length, width and the mean slip of the faults. Following the suggestion of Métivier et al. (2014), we used the source scaling law derived by Yen and Ma (2011) to compute the values of the lengths, widths and mean slips. Then, we calculated the cumulative coseismic changes in the Earth's mean radius (the so-called expansion rate) due to the overall events with different magnitudes (Fig. 3), where we assumed that the Earth is a perfect sphere. The change rate of the Earth's mean radius was estimated by adopting the un-weighted least-squares approach, which is equivalent to determining the cumulative change rate using the time-average method.

Considering that we did not know which nodal plane corresponds to the actual fault plane, we calculated the change rates of the Earth's mean radius of the solutions for both nodal planes of each earthquake. The results of the two sets of solutions seem consistent with each other, and the cumulative change was up to 0.8 mm. Based on the least-squares approach, the change rate from 1976 to 2014 was 0.02 mm/yr and the change rate during the past ten years was 0.06 mm/yr.

4. Effects of earthquakes of different magnitudes and types

Earthquakes of different types produce different effects on the Earth's mean radius. The energy released by thrust-type earthquakes is larger than the energy released by normal-type earthquakes, and thrust-type earthquakes should have a more significant influence on the expansion of the Earth than normal-type earthquakes. Based on the above consideration, we numbered the earthquakes of different types and computed the cumulative changes in the Earth's mean radius due to the different types of earthquakes (Fig. 4) in the last 40 years.

The number of thrust-type earthquakes was approximately 23,289, which was larger than the number of normal-type earthquakes (16651). The cumulative change in the Earth's mean radius due to the thrust-type earthquakes was 1.06 mm, and the