Evidences of the expanding Earth from space-geodetic data over solid land and sea level rise in recent two decades

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\textbf{Abstract}

According to the space-geodetic data recorded at globally distributed stations over solid land spanning a period of more than 20-years under the International Terrestrial Reference Frame 2008, our previous estimate of the average-weighted vertical variation of the Earth's solid surface suggests that the Earth's solid part is expanding at a rate of 0.24 ± 0.05 mm/a in recent two decades. In another aspect, the satellite altimetry observations spanning recent two decades demonstrate the sea level rise (SLR) rate 3.2 ± 0.4 mm/a, of which 1.8 ± 0.5 mm/a is contributed by the ice melting over land. This study shows that the oceanic thermal expansion is 1.0 ± 0.1 mm/a due to the temperature increase in recent half century, which coincides with the estimate provided by previous authors. The SLR observation by altimetry is not balanced by the ice melting and thermal expansion, which is an open problem before this study. However, in this study we infer that the oceanic part of the Earth is expanding at a rate about 0.4 mm/a. Combining the expansion rates of land part and oceanic part, we conclude that the Earth is expanding at a rate of 0.35 ± 0.47 mm/a in recent two decades. If the Earth expands at this rate, then the altimetry-observed SLR can be well explained.

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1. Introduction

Whether the Earth is expanding is a controversial problem in science. Although many scientists hold the opinion that during the geological time the Earth remains stable without obvious expanding or contracting [1,2], many paleontological, paleomagnetic, paleoclimatological, geological and geodetic evidences support the expanding Earth hypothesis [3–9].

Wilson [10] declared that the Earth is expanding based on geological evidences and Wegener’s continental drift hypothesis. Creer [11] concluded that the Earth’s radius $R_E$ was $0.55R$ at the early Precambrian (ca. 3800 million years (Ma) ago) and increasing ever since. Carey [4,12] suggested that the Earth was expanding within the ocean-floor expansion framework. Scalera [13,14] believed the Earth was expanding at a rate of few millimeters or fraction of millimeter per year from a series study of three palaeogeographical reconstructions for the Paleocene.

In the present study, we use two kinds of evidences to further estimate the Earth expansion rate. First, based on the space-geodetic data of 629 space-geodetic stations under the International Terrestrial Reference Frame (ITRF) 2008 (including stations of GPS, SLR, VLBI, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)) covering a period about 20 years [17–19] (All of the ITRF2008 files and results are available at the ITRF web site: http://itrf.ign.fr/ITRF_solutions/2008/), we found that the Earth’s radius was increasing at a rate about 0.24 mm/a [16]. However, this evidence only suggests that the solid part of the Earth is expanding.

The second evidence is the observation of sea level rise (SLR). Current observations show that the global mean SLR is at a rate of about 3.3 ± 0.4 mm/a from 1993 to 2009 [20] or 3.2 ± 0.4 mm/a from 1993 to 2013 [21]. It is mainly attributed to ice cap melting and temperature change of the sea. However, the Earth expansion may also contribute to the SLR, for the ice cap melting and temperature increase could not close the observed amount of SLR, namely, the SLR caused by the ice cap melting plus the thermal expansion is not balanced to the observed SLR by altimetry. In this study, to improve our previous study [16], we use SLR evidence to further estimate the Earth expansion rate.

2. Evidence from space-geodetic data

The Earth’s volume will increase if the Earth is expanding. Since the topography variation on the Earth's surface cannot be well modeled by the current distribution of space-geodetic stations, we consider the average vertical velocity of the Earth's surface rather than the actual volume of the Earth. First, a Delaunay triangulation Irregular Network [22,23] is set up by all of the geodetic stations. The average vertical velocity of the Earth’s surface could then be calculated as [16].

$$v_E = \frac{1}{N} \sum_{i=1}^{N} \frac{P_i v_i}{\sigma_i^2}$$

where $v_E$ is the expanding rate of the Earth, $v_i$ the representative vertical velocity of the $i$th triangle, $N$ the number of triangles, $P_i$ the spherical area of the $i$th triangle, $\sigma_i^2$ the variance of the $i$th triangle, and inversely proportional to the variance $\sigma_i^2$ of $v_i$.

The velocity of each triangle $v_i$ is calculated by [16]

$$v_i = \frac{1}{3} (v_D + v_E + v_F)$$

where $v_D$, $v_E$, and $v_F$ are vertical velocity of three nodes of this spherical triangle.

The data used are from ITRF2008, including coordinates and velocities of 1572 stations distributed over solid land (see Fig. 1). Of these sites, some sets of records actually refer to the same stations but in different time periods. In our calculations, the velocity and position of any one of such kinds of stations are determined by continuation of the corresponding data set over the whole time periods. Besides, many stations from different techniques locate in a very small area. These stations are merged to one station. The velocity and position of this new station is the average value of all the stations locating in this small area. After above handling, we have 845 stations left [16].

Absolute values of vertical velocities of some stations are relatively large. We consider that a too large vertical velocity should be related to local events rather than global expansion. Such stations are removed from our calculations. Stations locating in orogen belts are also removed since these vertical velocities of these stations are more likely related to local deformations but expansion. The information of orogen belts is provided by Bird [24]. After removing the above mentioned stations, 629 stations are used in our calculations based on DTIN. Details are referred to Shen et al. [16].

Post glacial rebound (PGR) is a possible reason for the vertical movement of the station. Based on the data released from website (http://grce.jpl.nasa.gov/data/pgr/) [25], the estimated average uplift rate $v_u$ of the whole surface of the Earth caused by the PGR is only $v_u = (5.69 \times 10^{-6} \pm 1.09 \times 10^{-6})$ mm/a. To obtain a more reasonable result of the influence of PGR on the uplift of the surface of the Earth, it is necessary to calculate the uplift rate for each space-geodetic station. In our study [16], we expand the grid data of uplift rate of the lithosphere into spherical harmonic coefficients, and then the uplift rate resulted from PGR could be calculated by the following equation

$$v_{PGR} = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \frac{c_{n0}^p}{P_{n0}^{\theta}(\theta)} + \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \frac{c_{nm}^p \cos m\lambda + s_{nm}^p \sin m\lambda}{P_{nm}^{\theta}(\theta)}$$

where $c_{n0}^p$, $c_{nm}^p$, and $s_{nm}^p$ are spherical harmonic coefficients obtained from grid values of uplift rate from PGR model [25], $P_{n0}^{\theta}(\theta)$ and $P_{nm}^{\theta}(\theta)$ are normalized Legendre functions defined in geophysical convention.
The expansion rate $a_{\text{land}}$ over land using 629 stations and that with PGR effect being considered are listed in Table 1.

### 3. Sea level rise and estimate of oceanic thermal expansion

According to current satellite altimetry observation, the SLR is at the rate of about $3.2 \pm 0.4$ mm with PGR effect considered in recent two decades [21]. It is considered that the observed SLR is mainly due to two causes [26]. The first is the ice cap melting, which makes the water originally stored on land flow into the sea. The second is the thermal expansion due to the fact that the global temperature increases [27] and the water becomes warmer [28]. The ice cap melting over land in recent two decades generates $1.8 \pm 0.5$ mm/a of SLR [29].

In this section, we estimate the oceanic thermal expansion based on the temperature change of the sea water. The temperature varies among various oceans and various depths. However, the sea water has following properties: first, the up-surface water layer of 200 m is uniform; second, water layer between 200 m and 1000 m decrease linearly; third, at the depth of 1000 m, the temperature achieves $4^\circ\text{C}$, and below that depth the water is little influenced by the temperature increase/decrease of the upper water. The current temperature of global average up-surface layer water is $17.4^\circ\text{C}$ (http://www.windows2universe.org/earth/Water/temp.html). And the global climate temperature increases $0.13^\circ\text{C}$ per decade in the last half century [26].

The sea water is divided into ten layers from surface to 1000 m depth, with each layer being 100 m thickness. The temperature of each layer is uniform all over the world. The temperature in first two layers (until 200 m depth) is uniform and it decreases linearly from the 200 m to 1000 m depth (see http://www.windows2universe.org/earth/Water/temp.html), we set the temperature of the first layer and second layer $T_1 = T_2 = 17.4^\circ\text{C}$, then we have

$$T_i = 17.4 - \frac{17.4 - 4.0}{5}(i - 2)(i = 3, 4, ..., 10)$$

(4)

The value of each $T_i$ is listed in Table 2. The SLR contributed by thermal expansion can be expressed as

$$a_{\text{thermal}} = \sum_{i=1}^{10} \gamma_i \delta T_i h$$

(5)

where $\gamma_i$ is the water expansion coefficient of the $i$th layer, which is listed in Table 2 (http://physchem.kfunigraz.ac.at/sm/Service/Water/H20thermexp.htm). $\delta T_i$ is the temperature increase of the $i$th layer in the last century, $h$ is the thickness of each layer (see Table 2). To make an optimistic estimate, we set the temperature increase of the first and second layer $\delta T_1$ as $0.13^\circ\text{C}/\text{d}$, the temperature increase below the last layer is $0^\circ\text{C}/\text{d}$. Then based on linear interpolation we have

$$\delta T_i = 0.13 - \frac{0.13}{5}(i - 1)(i = 2, 3, ..., 10)$$

(6)
Water expansion coefficients correspond to Sea level rise observations, unbalanced SLR, Earth expansion and balanced SLR in recent two decades. Hence, the SLR contributed by thermal expansion is estimated as 0.35 mm/a. Over land and ocean, the whole Earth expansion rate is estimated as 0.47 mm/a in recent two decades. This study, using space-geodetic data under ITRF2008 over land and sea level rise evidence over ocean, we suggest that the Earth expands at a rate about 0.2 mm/a in recent two decades. The accuracy is low because the SLR evidence has low accuracy. Inversely, if the Earth expands at a rate about 0.35 ± 0.47 mm/a, the present observations and estimates over ocean could be well balanced: altimetry result 3.2 mm/a (with PGR effect considered) is almost equal to 3.15 mm/a (3.15 mm/a = ice melting contribution 1.8 mm/a + thermal expansion effect 1.0 mm/a + Earth expansion rate 0.35 mm/a).

In this study, the salinity variation effect is not considered, which contribute less than 0.1 mm/a. The thermal expansion effect below 1000 m depth is neither considered, which contribute also less than 0.1 mm/a. We note that below 2000 m depth, with the temperature increase, the thermal expansion is negative (i.e., the “thermal expansion effect” is in fact a contraction effect below 2000 m depth [30]). Since the accuracies of the ice melting estimate and the thermal expansion estimate are quite low, it is not necessary to consider the salinity variation effect and deep ocean water thermal expansion (contraction) effect. This study is a further improvement of our previous study. Deliberate and thorough study about the SLR balance and estimate of the Earth expansion rate will be investigated in a separated paper. Finally, we note that using space-geodetic data (GPS sites over the globe) Wu and his colleagues [31] suggested that space-geodetic observation does not support the Earth expansion hypothesis. A relevant comment about this suggestion is addressed elsewhere [32].

### 5. Discussions and conclusions

Based on space-geodetic data (ITRF2008) and temporal gravity data, our previous study [16] suggests that the Earth expands at a rate about 0.2 mm/a. In this study, using space-geodetic data under ITRF2008 over land and sea level rise evidence over ocean, we suggest that the Earth expands at a rate about 0.35 ± 0.47 mm/a in recent two decades. The accuracy is low because the SLR evidence has low accuracy. Inversely, if the Earth expands at a rate about 0.35 ± 0.47 mm/a, the present observations and estimates over ocean could be well balanced: altimetry result 3.2 mm/a (with PGR effect considered) is almost equal to 3.15 mm/a (3.15 mm/a = ice melting contribution 1.8 mm/a + thermal expansion effect 1.0 mm/a + Earth expansion rate 0.35 mm/a).

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### Table 2 – Water expansion coefficients correspond to different temperature and temperature increase of different layers.

<table>
<thead>
<tr>
<th>ith layer</th>
<th>Average temperature (°C)</th>
<th>Temperature increase δTᵢ (°C/da)</th>
<th>Water expansion coefficient γᵢ (10⁻⁶/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 1, 2 (0–100 m)</td>
<td>17.4</td>
<td>0.130</td>
<td>179</td>
</tr>
<tr>
<td>i = 2 (100–200 m)</td>
<td>17.4</td>
<td>0.117</td>
<td>179</td>
</tr>
<tr>
<td>i = 3 (200–300 m)</td>
<td>15.9</td>
<td>0.104</td>
<td>161</td>
</tr>
<tr>
<td>i = 4 (300–400 m)</td>
<td>14.4</td>
<td>0.091</td>
<td>143</td>
</tr>
<tr>
<td>i = 5 (400–500 m)</td>
<td>12.9</td>
<td>0.078</td>
<td>124</td>
</tr>
<tr>
<td>i = 6 (500–600 m)</td>
<td>11.4</td>
<td>0.065</td>
<td>106</td>
</tr>
<tr>
<td>i = 7 (600–700 m)</td>
<td>10.0</td>
<td>0.052</td>
<td>88</td>
</tr>
<tr>
<td>i = 8 (700–800 m)</td>
<td>8.47</td>
<td>0.039</td>
<td>66</td>
</tr>
<tr>
<td>i = 9 (800–900 m)</td>
<td>6.98</td>
<td>0.026</td>
<td>45</td>
</tr>
<tr>
<td>i = 10 (900–1000 m)</td>
<td>5.49</td>
<td>0.013</td>
<td>24</td>
</tr>
</tbody>
</table>

Substituting equation (6) into equation (5), and using the relevant values, we have

\[ a_{\text{thermal}} = 100 \times (179 \times 0.13 + 179 \times 0.117 + 161 \times 0.104 + 143 \times 0.091 + 124 \times 0.078 + 106 \times 0.065 + 88 \times 0.052 + 66 \times 0.039 + 45 \times 0.026 + 24 \times 0.013) \times 10^{-6} = 0.99 \text{ mm/a} \]  

and the corresponding accuracy is estimated as ±0.2 mm/a. Hence, the SLR contributed by thermal expansion is estimated as 1.0 ± 0.2 mm/a.

### 4. Estimate of the Earth’s expansion

Based on the altimetry-observed result (3.2 ± 0.4 mm/a) and ice melting estimate (1.8 ± 0.5 mm/a) in recent two decades (see Table 3), the Earth expansion rate over ocean region in recent two decades is estimated as

\[ a_{\text{ocean}} = (3.2 – 1.8) \pm \sqrt{0.4^2 + 0.5^2} = 0.4 \pm 0.67 \text{ mm/a} \]  

According to equation (8), though the accuracy is very low, the expansion rate over ocean region is comparable with the expansion rate over land. Combining the expansion rates over land and ocean, the whole Earth expansion rate is estimated as 0.35 ± 0.47 mm/a, as listed in Table 3. This estimate is a weighted result with taking the area as weight, namely

\[ \alpha = \frac{P_{\text{ocean}} a_{\text{ocean}} + P_{\text{land}} a_{\text{land}}}{P_{\text{ocean}} + P_{\text{land}}} \]  

and the corresponding accuracy is estimated as

\[ \nu_\alpha = \left( \frac{P_{\text{ocean}}^2 \nu_{a_{\text{ocean}}}^2 + P_{\text{land}}^2 \nu_{a_{\text{land}}}^2}{P_{\text{ocean}} + P_{\text{land}}} \right)^{1/2} \]  

where \( P_{\text{ocean}} = 70\% \) and \( P_{\text{ocean}} = 30\% \).

### Table 3 – Sea level rise observations, unbalanced SLR, Earth expansion and balanced SLR in recent two decades.

<table>
<thead>
<tr>
<th>Entities</th>
<th>Variation rate (mm/a)</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altimetry of SLR</td>
<td>3.2 ± 0.4</td>
<td>CU/CSIRO/NASA/GSFC/NOAA (2014)</td>
</tr>
<tr>
<td>Ice melting contribution to SLR</td>
<td>1.8 ± 0.5</td>
<td>Meier 2007 [29]</td>
</tr>
<tr>
<td>Thermal expansion contribution to SLR</td>
<td>1.0 ± 0.2</td>
<td>This study</td>
</tr>
<tr>
<td>Unbalanced SLR amount</td>
<td>0.4 ± 0.67</td>
<td>This study</td>
</tr>
<tr>
<td>Radial average variation in land part (( a_{\text{land}} ))</td>
<td>0.24 ± 0.05</td>
<td>Shen et al. [16]</td>
</tr>
<tr>
<td>Radial average variation in ocean part (( a_{\text{ocean}} ))</td>
<td>0.4 ± 0.67</td>
<td>This study</td>
</tr>
<tr>
<td>Radial average variation in whole Earth (( \delta ))</td>
<td>0.35 ± 0.47</td>
<td>This study</td>
</tr>
<tr>
<td>Balanced SLR amount</td>
<td>0.05 ± 0.82</td>
<td>This study</td>
</tr>
</tbody>
</table>
Acknowledgments

We thank two anonymous reviewers’ comments and suggestions, which improved this manuscript. This study is supported by National 973 Project China (2013CB733305, 2013CB733301), National Natural Science Foundation of China (41174011, 41429401, 41210006, 41128003, 41021061).

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