Change in the sea surface height observed by satellite altimetry before and after the 2004 Sumatra-Andaman earthquake

by

Yutaka Hayashi[1], Nobuo Hamada[2], Tsurane Kuragano[3], Toshiyuki Sakurai[4], Hiromi Takayama[5], Yohei Hasegawa[6] and Kenji Hirata[7]

ABSTRACT

The coseismic geoid change associated with the 2004 Sumatra-Andaman earthquake has been observed for the first time by satellite altimetry from Jason-1 and TOPEX/Poseidon. We estimated that the peak-to-peak change in sea surface height before and after the earthquake was 7±3 cm. Both peaks were estimated to be located approximately 50km and 120km from the Sunda Trench. These peaks possibly indicate the upper and lower edges of the averaged location of a high-slipped area in the entire earthquake fault. This is because from a calculation based on the dislocation theory, the two peaks of amount change of geoid height are theoretically predicted to locate almost above the upper and lower edges of the faults in the case of a shallow long thin low-angle reverse fault.

We also draw attention to the fact that satellite observations have the potential to detect new phenomena accompanying huge earthquakes, and they can improve our seismological knowledge.

KEYWORDS: asperity, fault location, Jason-1, satellite altimetry, coseismic geoids change, TOPEX/Poseidon, the 2004 Sumatra-Andaman earthquake

1. INTRODUCTION

The 2004 Sumatra-Andaman earthquake, which brought the tsunami in the Indian Ocean on December 26, was a coupled earthquake along the Sunda Trench subduction zone[1]. This earthquake was too huge to be observed accurately by seismometers. Although the size of the main shock is a crucial issue that is still being discussed, an 11-m slip on a fault with a length of 1200 km and width of 200 km wide (moment magnitude Mw = 9.3) has been estimated from the earth's normal modes [2]. This estimation implies that of all the earthquakes in recorded history, the 2004 Sumatra-Andaman earthquake was the second largest after the 1960 Chilean earthquake (Mw = 9.5 [3]).

Gravity potential field and absolute gravities can change due to disturbances in the gravity field resulting from the mass redistribution caused by an earthquake. Unfortunately, the changes in gravity caused by the 2004 Sumatra-Andaman earthquake are considered to be too small to be sampled through both the ongoing gravity mission with the GRACE (Gravity Recovery and Climate Experiment by NASA) satellite and the future mission of the European Space Agency with the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) satellite [4].

On the other hand, the coseismic geoid change accompanying an earthquake with a magnitude 9 is theoretically expected to be of the order of centimeters [5]. The fact that geoid heights are almost equal to the average sea surface heights enables satellite altimetry to detect coseismic geoid changes through the observation of changes in sea surface heights [6].

Although this prospect appears paradoxical, it is very probable that oceanographic missions with satellite altimeters can investigate gravity fields disturbed by huge earthquakes to a greater extent

1 Researcher, The 1st Laboratory, Seismology and Volcanology Research Department, Meteorological Research Institute, 1-1 Nagamine, Tsukuba 305-0052, Japan.
2 Director, Sapporo District Meteorological Observatory, N2W18-2, Chuo-ku, Sapporo 060-0002, Japan.
3 Forecaster, Office of Marine Prediction, Marine division, Global Environment and Marine Department, Japan Meteorological Agency, Otemachi 1-3-4, Chiyoda-ku, Tokyo 100-8122, Japan.
4 Engineering Officer, Office of Marine Prediction, ditto.
5 Head, The 1st Laboratory, as same as 1.
6 Chief Researcher, The 1st Laboratory, ditto.
7 Research Scientist, Program for Deep Sea Research, IFREE, Japan Agency for Marine-Earth Science and Technology, Natsushima 2-15, Yokosuka 237-0061, Japan.

than gravity missions (Fig.1). We focused on the observation of sea surface heights by the satellite altimetry in the seismic zone of the 2004 Sumatra-Andaman earthquake. In particular, we attempted to detect coseismic geoid changes in order to find out information on the fault mechanism.

2. METHODS

2.1 Data

A satellite altimetry is a microwave radar for measuring the distance to the sea surface directly below. It is equipped on satellites whose tracks can be controlled and analyzed with high accuracy (Fig.2).

(1) Altimeters

We used observation data from altimeters on TOPEX/Poseidon and its successor Jason-1 (by NASA, USA and CNES, France). Both satellites are operated under 10-day cycles.

Observed sea surface heights are routinely processed by NASA to eliminate effects of geoid locality, ocean tides, air pressure and atmospheric vapor. The processed data is freely available to users. The calculated sea surface height is considered to be the results of the combination of effects of sea currents, temperature of the sea, surface, wind on the sea, other oceanic physical phenomena, and errors. According to NASA's "Fact Sheets," the accuracies of the observations are 4.2 cm for TOPEX/Poseidon and <4.2cm (required) and <2.5 cm (goal) for Jason-1.

(2) Period

We used data from November 4, 2004, to February, 16, 2005, with the exception of December 26, 2004.

We did not use data of December 26, 2004 in order to exclude effects of the tsunami by the 2004 Sumatra-Andaman earthquake. In fact, the propagating tsunami in the Indian Ocean was detected by altimeters on TOPEX/Poseidon and Jason-1 approximately 2 h after the occurrence of the earthquake [7].

(3) Area

We limited the area to be analyzed to a belt-like shape with a length of over 1000 km, as shown in Fig. 3. The eastern and western edges of this area are 300 km east and 150 km west of the Sunda Trench [8], respectively. The northern and southern edges are determined to the extent of aftershock region by USGS/NEIC until February, 16, 2005.

2.2 Quality control

(1) Resampling

We resampled data at latitude intervals of 0.05 degree. In this study, then, we use only sampling points that include three or more observations and that include one or more observations before and after the main shock.

The distributions of the available sampling points are shown in Fig. 3.

(2) Estimation of background level

We defined a BGL (background level) at every sampling point as the difference between the average value and a quartile determined by the assumption that observation data follow a normal distribution.

2.3 Data processing

(1) Calculation of change in sea surface height

The dSSH (difference in sea surface height) at every available sampling point is calculated as the differences between the averaged sea surface height after the main shock (until February 16, 2005) and that before (from November 4 2004).

(2) Relation between distance and change in sea surface height

Averaged dSSHs are calculated at every 10 km in the range of -150 km to 300 km from the Sunda Trench. The signs of the distance refer to the location of the observation points with respect to the trench (negative: west; positive: east). They are weighted average depending on the number of observations of each point in the belt-like area with a width of 20 km and length of over 1000km. The averaged dSSH at 50 km from the Sunda Trench is defined as the average of dSSHs at all sampling points falling within a distance of 50± 10 km from the trench. The effects of the background are also estimated from BGLs at each sampling point in the area using the error transfer theory.

3. RESULTS

The dSSH before and after the 2004 Sumatra-Andaman earthquake are shown against distance from the Sunda Trench in Fig. 4. The analysis includes fluctuation of the order of several centimeters in the dSSH.

Two peaks are obtained east to the trench at 50 km (+1.2±1.1cm) and 120 km (-5.7±2.3cm). Therefore, the resulting peak-to-peak value is 7±3cm. The following effects are included in this value; (1) various effects by oceanic physical phenomena other than those of the earthquake, (2) post-seismic effects, and (3) errors caused by the accuracy of the satellite altimeters.

4. DISCUSSIONS

4.1 Theoretical coseismic geoid change

Equations have been established to estimate the coseismic geoid change by a finite fault using the dislocation theory [5]. One example of our calculation using the equations is shown (Fig. 5).

The calculated coseismic geoid change by a shallow long low-angled reverse fault model whose moment is equivalent to Mw 9.3 has the following characteristics.

(a) The geoid change is more dependent on the component of the width axis than on that of the length axis in the position coordinates.
(b) The two peaks of the geoid change in the width-axis cross section are located almost right above the upper and lower edges of the faults.
(c) The peak-to-peak geoid change reaches several centimeters.

4.2 Interpretation of results

The peak-to-peak sea surface height in the aftershock region changed by 7±3cm. The size and distribution pattern of the observed change in the sea surface height east of the trench (in Fig. 4) were in some agreement with the calculated coseismic geoid change (box on the right in Fig.5). In general, the geoid height is approximately equal to the sea surface height. Therefore, a change in the geoid height would be approximately equal to the averaged sea surface height.

As discussed above, a shallow long low-angled reverse fault results in two peak values (one is plus, the other is minus) of the change in the geoid height, which are located almost right above the upper and lower edges of the faults. Then, we conclude that the observed peak locations (50 and 120km east of the trench) possibly indicate the limits of a high-slipped area in the main shock fault plane, on the basis of the averaged seismic image through the entire fault along the Sunda Trench.

5. CONCLUSIONS

We found the coseismic geoid change caused by the 2004 Sumatra-Andaman earthquake in the data of the sea surface height obtained by satellite altimetry from Jason-1 and TOPEX/Poseidon. This is the first time that a coseismic geoid change has been observed. We conclude that approximate limits of the high-slipped area in the main shock fault plane in terms of averaged seismic images are 50 and 120 km east of the trench.

In addition, satellite altimetry also has the potential to contribute to tsunami studies because altimeters can directly detect the tsunami propagating in oceans. In fact, Jason-1 and TOPEX/Poseidon clearly captured the tsunami wave form in the Indian Ocean approximately 2 h after the 2004 Sumatra-Andaman earthquake [7]. A model with an extremely low rapture velocity (0.7km/sec) inferred from this satellite observation is also reported [9].

A wide-swath altimeter that can observe sea surface height distribution within a distance of 200 km will be equipped on Jason-2 (NASA, CNES; successor of Jason-1, launch planned for 2008). This new type of altimeter will provide an improved opportunity to observe tsunamis and coseismic geoid changes caused by huge earthquake in the future [10], and it will contribute toward enhancing seismological knowledge.

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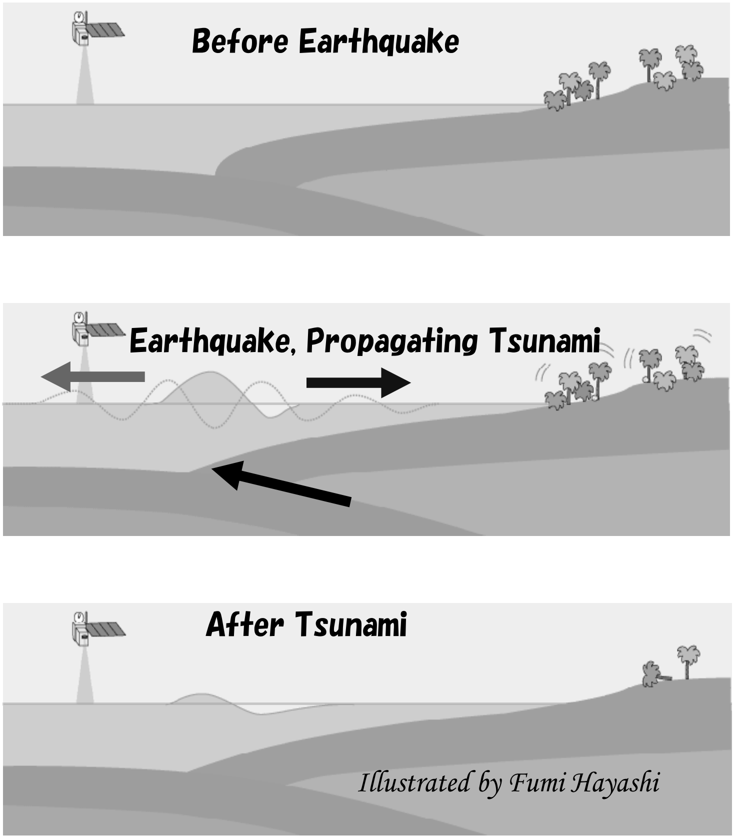

Fig.1 Propagating tsunamis and changes in sea surface heights caused by huge earthquakes might be observed.
Averaged sea surface heights (almost equal to geoid height) will be changed on account of the disturbed gravity field by mass redistribution caused by huge earthquakes. Propagating tsunamis and coseismic geoid changes might be observed if satellites are fortunate enough to have proper tracks.

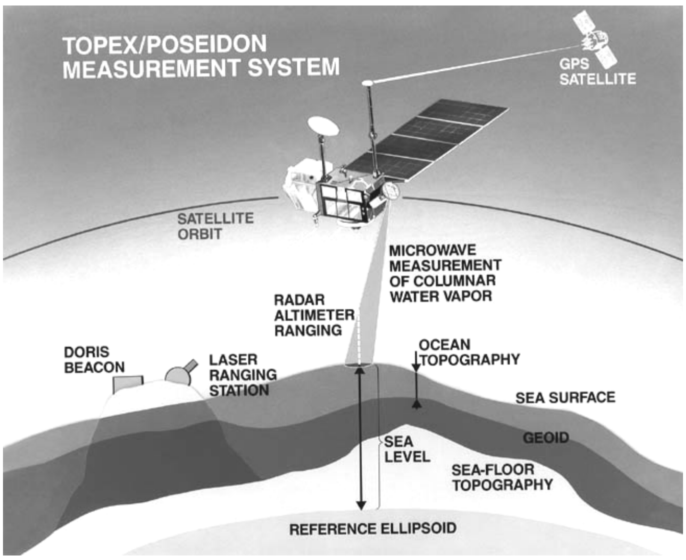

Fig.2 Measurement system of Satellite altimetry.
From NASA's website.

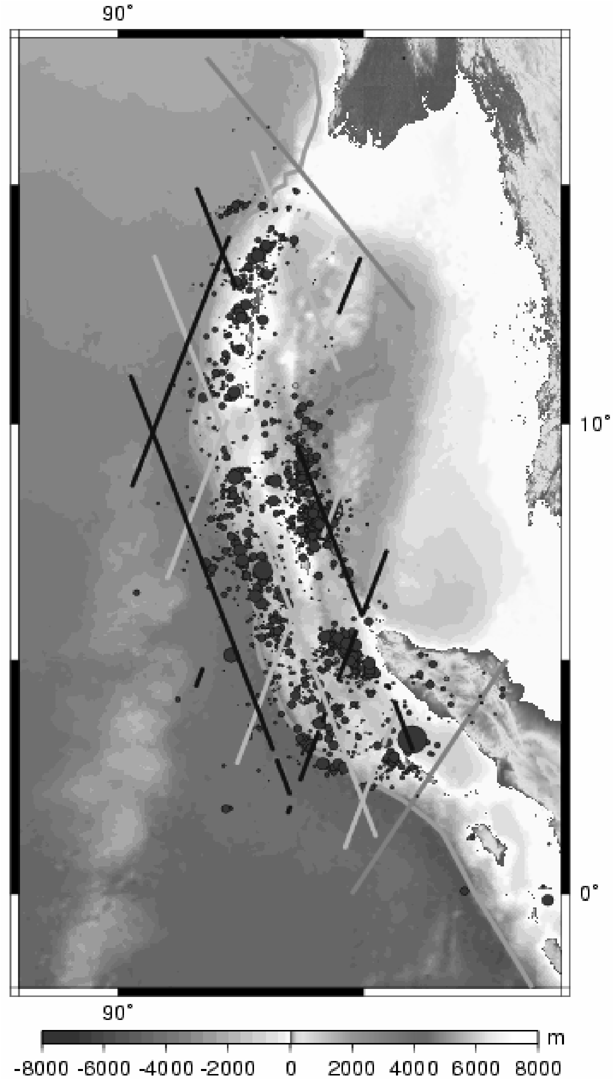

Fig.3 Area to analyze the change in sea surface heights before and after the 2004 Sumatra-Andaman earthquake.

The curved line indicates trenches [8]. The target area to be analyzed lies between the top and the bottom line. Lines in the target area show the distribution of the observation points on the tracks of Jason-1 and TOPEX/Poseidon. The epicenters (by USGS/NEIC) of the main shock and the aftershocks (M>=4.0) until February 16 2005 are also plotted with solid circles. ETOPO2 (by NGDC) is used for elevation and bathymetry data.

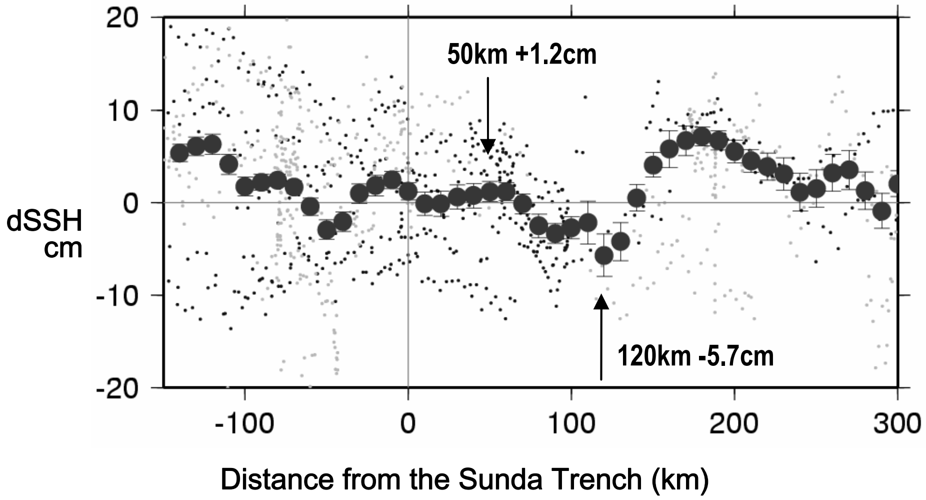

Fig.4 Relation between the Sunda Trench and change in sea surface height before and after the 2004 Sumatra-Andaman earthquake.

Signs of the distance refer to the side at which the observation points are located from the trench (negative: west, positive: east). "dSSH" is defined as the averaged sea surface height after the main shock (until February 16 2005) minus that before (from November 4 2004). Small dots indicate each data at the sampling point. Large dots with error bars indicate averaged dSSHs over a 20km width and background levels. (e.g.: dSSH at 50 km from the Sunda Trench is defined as average of dSSH at all sampling points falling within 50±10 km distant from the trench.) Background levels of each peak at 50km and 120 km are 1.1 cm and 2.3 cm.

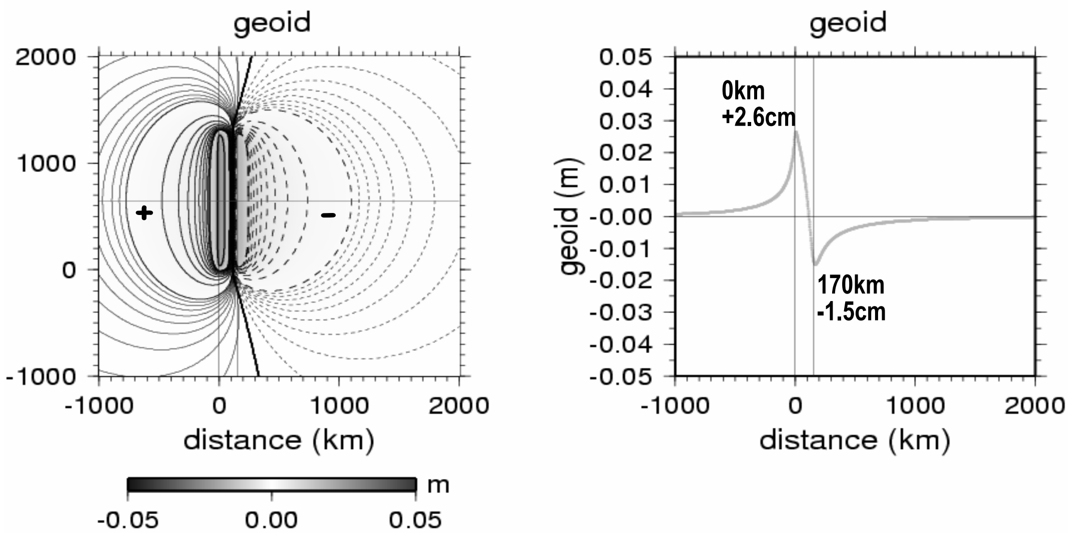

Fig.5 Calculated coseismic geoid change by a shallow long low-angled reverse fault model whose moment is equivalent to Mw 9.3.

Distribution of coseismic geoid change calculated by dislocation theory [5] (left) and its cross section along the line parallel to x-axis passing through the center of the fault (right).

Parameters: length, 1300 km; width, 150 km; depth of the upper edge, 10 km; dip, 10 degree; slip, 14 m; rake, 90 degree; density of crust, $2.67\times10^3 kg/m^3$.