A NEW APPROACH FOR THE TSUNAMI PREDICTION USING SATELLITE ALTIMETRY: TRIALS FOR ACEH TSUNAMI EVENTS IN 2004 AND 2005

SUSUMU KANNO", YASUO FURLSHIMA[3], I WAYAN NUARSA[1], I GEDE HENDRAWAN[1]

Abstract

Change in the sea surface height anomaly derived from satellite altimeter was examined and applied to evaluate the possibility of tsunami prediction before the occurrence. Sea surface height anomaly was composed period during earthquake and tsunami occurrence. Daily variability in the sea surface height anomaly was traced about the location of hypocenler, aftershock, and the end of earthquakes from satellite altimctry. Results shows that there are the locations where the sea surface height anomaly suddenly increased or decreased before tsunami occurrence in hypocenter or aftershock area and these trends appeared one day before tsunami event at least. This result can be utilized and applied for the development in not only the tsunami monitoring system as the disaster monitoring, but also for the effective tsunami prediction system in the near future.

Keywords : tsunami, earthquake, bottom topography, sea surface height, satellite altimetry, altimeter, disaster prevention.

I. Introduction

Tsunami is a Japanese word which can translate to English as "harbor wave". It is represented by two characters, the first character, "tsu" means harbor, while the last character, "nami" means "wave". In the pasi hood, tsunami was sometimes referred to "tidal waves" by the general public and "seismic waves" by the scientific field. The term "tidal wave" is a misnomer; although the tsunami's impacts on the coastline are dependent on the tidal level at the time of tsunami strikes, tsunamis are not related to the tides. Tides result from the imbalance, extraterrestrial, gravitational influences of the moon, sun. and planets. The term, "seismic wave" is also misleading. "Seismic" implies an earthquake-related mechanism and tsunami also occur by the non-seismic event such as landslide and meteorite impact.

Tsunami has been measured from long time ago by several in-situ instrumentations as tidal station, super sonic or laser tsunami sensors, hydraulic pressure sensor, and GPS tsunami sensor, etc. These observational apparatuses can measure the tsunami with satisfactory accuracy, but they have a few spatial coverage. Therefore, it is difficult to obtain the information on tsunami in wide area of the coastal region. Recent days, satellite remote sensing is well known as a useful tool for coastal monitoring and has been routinely used to estimate the disaster of tsunami strike in coastal area with wide spatial coverage. There are two main categories of remote sensing concerning with estimation of the degree in the disaster made by tsunami: (1) detection of the disaster area by optical sensor which can provide the true or false color images and

I.Cailcr for Remote Sensing and Ocean Science (CreSOS). Udayana University, Dcnpasar, Bali Indonesia.
2. Kvowa Concrete Industry Co.. Ltd Center.
3. JJCUII Agency for Marine Science and Tcchno!t>gy.

(2) evaluation of the disaster by the score using active microwave sensor as synthetic aperture radar(SAR). The optical sensor has been supplying effective information on disaster area by the change in spectrum between pre-event and post event of tsunami derived from the wash out or destruction of the land objects and the topographic change. Nohjima (2004) showed that the degree of damage on building by natural disaster can be estimated by the composite value which defined from the difference of backward scattering coefficient of active microwave between before and after the disaster in the artificial building area. This method was utilized to the estimation of the damage for the building in city area about Hyogo Earthquake, occurred in 1995 and the result showed reasonable agreement between the estimation and actual situation of the damage. Thus, . t h e remote sensing applications are useful and can provide important information from a view point of the disaster prevention. But on the other hand, satellite remote sensing system has immediacy for observation to synchronize it to tsunami event. For example, the frequency of the satellite over flight is one day order in most of case. Even most frequent satellite, NOAA has the frequency about four times of over flight in a day. Add to this, even if satellite can detect the tsunami synchronized with the occurrence, the disaster can not be avoided and there is no measure to prepare the disaster prevention. If the tsunami occurrence can be detect before one day at least, several measure can be ready to save human life and their property. Tsunami is generated by abrupt deformation of sea floor and vertically displaces the overlying water. Tectonic earthquake is a particular kind of earthquake and is associated with the earth's crustal deformation; when these kind of earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position. Waves are formed instead of the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium. When large areas of the sea floor elevate or subside, a tsunami can be occurred.

Fig. 1. Locations of the large tsunami occurrence around Aceh, Indonesia in 2004 and 2005

Table 1. Outline of main tsunami event used in this study occurred around Aceh.

DATE	MAGNITUDE	HYPOCENTER	NUMBER OF VICTIM
Dec. 26*, 2004	9.3	Lat:3.316; Long:95.854	over 220,000
Mar. 28'h, 2005	8.7	Lat:2.065; Long:97.010	over 2,000

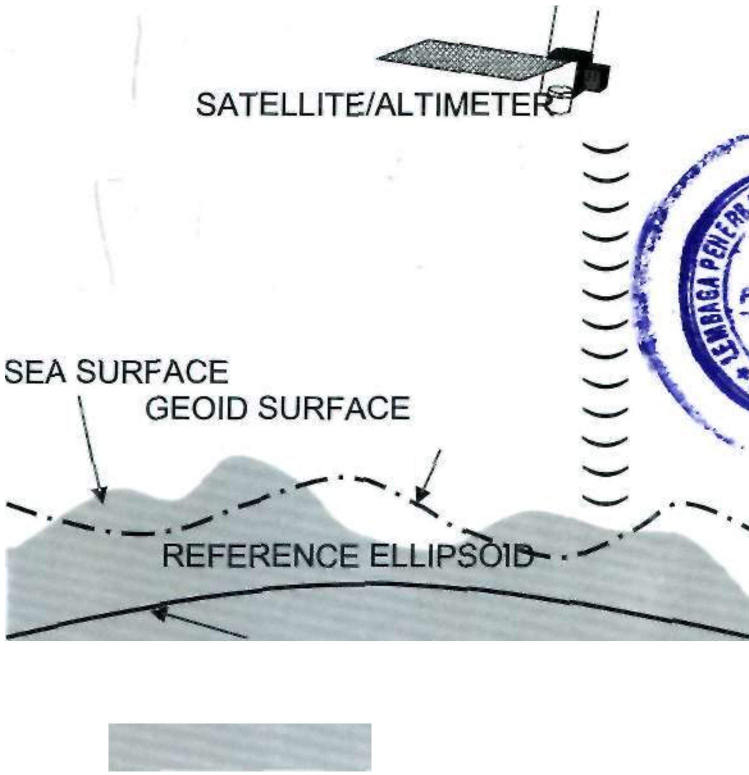

Fig. 2. Schematic representation of the concept for sea surface height measurement by satellite-borne altimeter

Based on these theories, in this paper the change in the sea surface topography is assumed as the beginning of tsunami and is traced in daily basis in the hypocenter, aftershock, and calm areas to discuss the possibility of tsunami prediction.

II. Data

Two large tsunami events occurred in the coastal area of northern Sumatra Island in 2004 and 2005 are examined to analyze the possibility of the tsunami prediction by satellite altimetry. In the morning of December 26, 2004, a magnitude of 9.3 Richter scale earthquake struck the northwest coast of the Sumatra Island, Indonesia. The earthquake was occurred with the complex slip on the fault where the oceanic portion of the Indian Plate slide under Sumatra, part of the Eurasian Plate. The earthquake made a deformation of the ocean floor and pushed the overlying water as the tsunami waves. The tsunami waves destroyed the adjacent coastal areas where the wave height was about 25 meters and killed nearly 300,000 people of the populations in the region and tourists from abroad. The tsunami waves traveled in the global scale and were measured in the Pacific Ocean and many other places by tide gauges. On 28 March 2005, after around three months from this event, an earthquake with an estimated of 8.7 Richter scale occurred off the western coast of Sumatra. It did not appear that a basin-wide tsunami was generated but the local tsunami damage has been reported at the Simeuleu Island located near Aceh area with over 2000 victims. Locations and outlines of these two tsunami events are shown in Fig. 1 and Table 1, respectively.

In order to trace the daily change of sea surface position, the sea surface height anomaly is used for the analysis and provided by the satellite-borne altimeter. The satellite altimeter measures the time required to transmit from the satellite sensor to sea surface, reflect from the surface and return to the sensor by radar pulse as shown in Fig. 2. The speed of the radar pulse depends on the dry air between the sensor and the sea surface, the water vapor in the atmosphere, and the electron content of the ionosphere. The distance from the sensor to the ocean surface is obtained after the correction of these kinds of the effects to the accuracy of a few centimeters. The reason of using the sea surface height anomaly, is that the normalization is required to detect actual change in the surface position in the study area. Since the swath of the satellite altimeter is not enough to cover the sufficient area around the event, several satellite altimeter data were composed for each daily images. The sea surface height anomaly images had to be merged and composed over the several images obtained by several satellite altimeters, such as Jason, TOPEX/POSEIDON, Geosat Follow-ON, ERS-2 and Envisat around objective date. Brief specifications of these satellite/altimeter are shown in Table 2.

Twenty one images were composed from the multiple satellite images provided from the satellite altimeters in Table 2 for the two tsunami events. The change in the sea surface height anomaly can be analyzed in 21 days time scale with the centering of event date in the period. The change in sea surface height anomaly is traced and analyzed by the extraction of the data from these images.

III. Results and Discussion

Some examples of these 21 images of the sea surface height anomaly are shown in Fig. 3 for each tsunami event. Three figures are corresponded to the tsunami occurred on December 26th 2004 (left) and March 28th 2005 (right). Three figures arranged from top to bottom can be distinguished as the day of before(A), just(B), and after(C) the tsunami event. Although these are just a comparison between three days images the significant change in sea surface height anomaly can be seen in the figure.

Table 2.Brief specifications of satellite-borne altimeter used for satellite altimetry in this)er.

SATELLITE/SENSOR	SAMPLING RATE	ORBIT HEIGHT	ACCURACY
Jason	10 days	1336 km	4.2 cm
TOPEX/POSEIDON	10 days	1336 km	4.2 cm
Geosat Follow-On	17 days	800 km	3.5 cm
ERS-2	35 days	777 km	10 cm
Envisat	35 days	799 km	12 cm

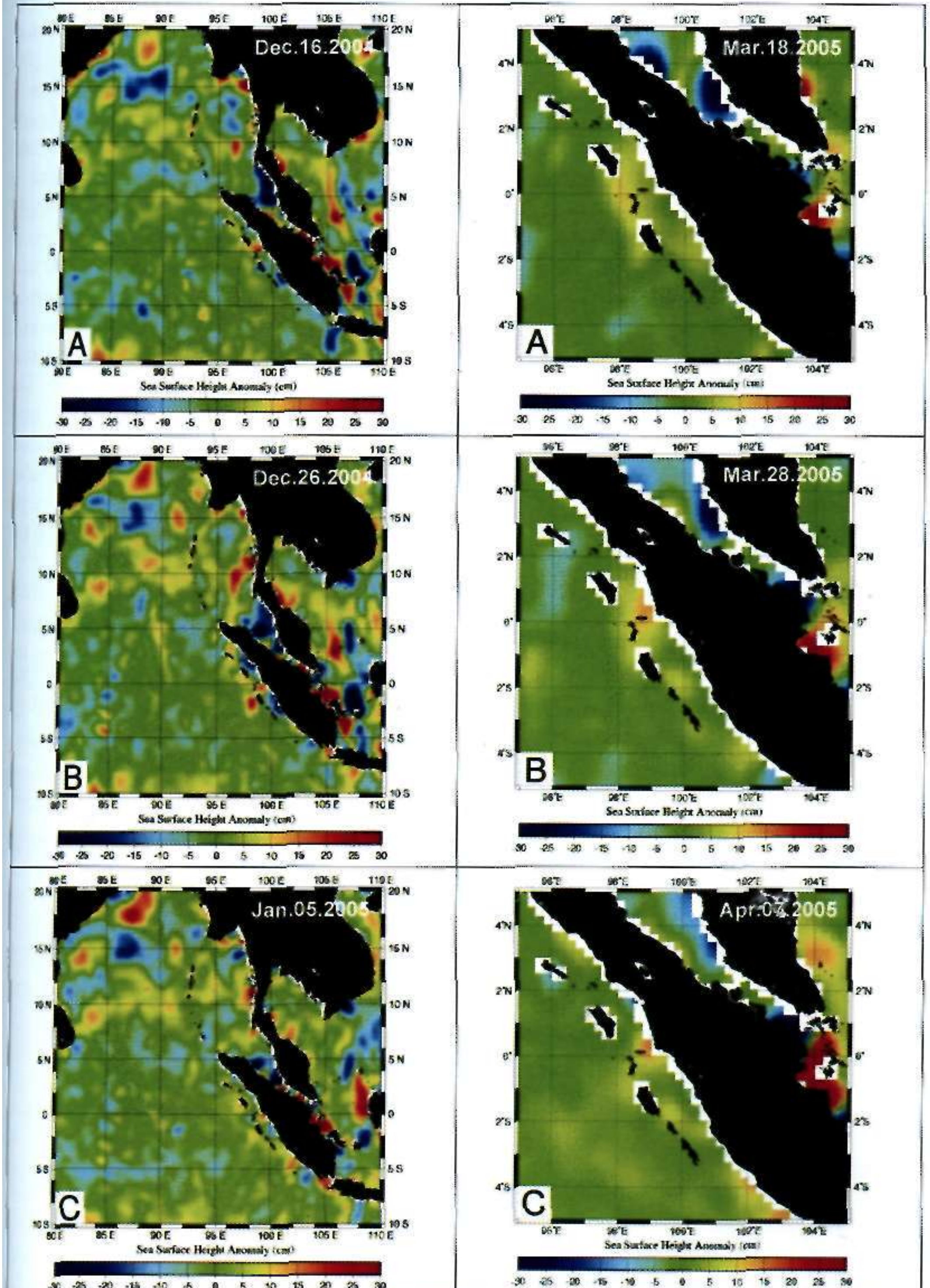

Fig. 3. Images of sea surface height anomaly obtained the date before(A), just(B), and after(C) the tsunami event. Left and right figures are corresponding to the event occurred on December 26th 2004 and March 28th 2005, respectively

Three kinds of the grids of one degree scale are defined to trace and analyze the change in sea surface height anomaly during the 21 days; (l)grid referred to the hypocenter of earthquake as the source power of the tsunami, (2)grid referred to the location of aftershock, and (3)grid without any earthquakes or the concerning events. These grids are indicated in Fig. 4 for both events. These grids are classified by the initial letter of grid index; (1) the initial letter "M" is referred to the grid including the hypocenter of the earthquake, (2) the initial letter "S" means that some aftershocks have occurred in that grid, and (3) the one of "R" is corresponded to the grid without any earthquake-concerning events. Here, the grids without earthquake are set for the reference to evaluate the difference of the time series of the sea surface height anomaly from the hypocenter and the aftershock areas. The sea surface height anomaly was averaged in each one degree grid and the time scale was traced for the grids.

Daily changes in sea surface height anomaly in the grids set according to above definition and several statistical values of the tsunami occurred on December 26th 2004 are shown in Fig. 5 and Table 3, respectively. The sea surface height anomaly is traced from December 16, 2005 to January 5th , 2005. This period is corresponded to the 10 days before to 10 days after the tsunami event. Each line in the figure is referred to the sea surface height anomaly of the grid as shown in legend. The trend of the daily change as a whole has few features, except the trend in the daily changes around hypocenter. The daily changes are not significant until December 24th 2004 but the sea surface height increases suddenly on December 25th 20054 and this high sea surface height is continued until January 1st 2005 for the time series of the hypocenter as drawn by solid line for grid "M". In addition, there are two grids which the sea surface height increases from December 24th 2004 in the grids of aftershock, "S-3" and "S-5". This trend is not so significant for the grid "S-5". However, the grid "S-3" shows a

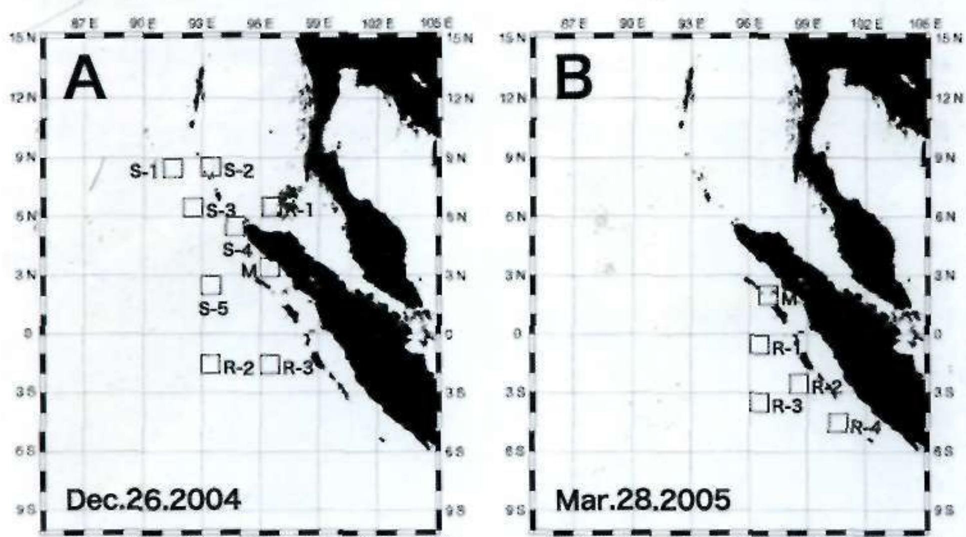

Fig. 4. Grids set for the trace of change in sea surface height anomaly from ten d: before to ten days after the tsunami events occurred on December 26th, 2004 (A) a March 28th, 2005 (B). Initial letters of the grid index, "M", "S", and "R" are defined the grid including hypocenter, aftershock, and no earthquake, respectively

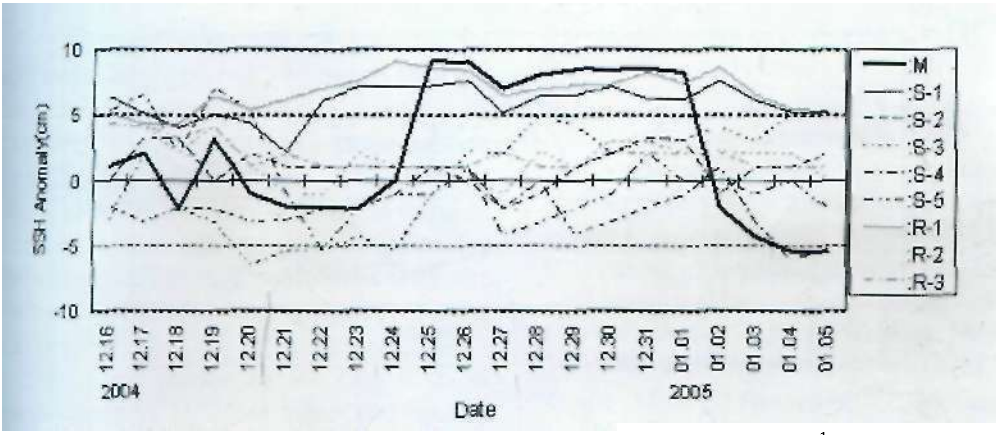

Fig. 5. Time series of sea surface height anomaly from December 16"1, 2004 to January 5th, 2005 for tsunami event on December 26lh, 2004. Each line can be referred to the time scale for the grid as shown in the legend.

Table 3. Results of the statistical analysis of sea surface height anomaly for each grid during time scale of the analysis for the event on December 26*, 2004.

Grid ID	M	S-l	S-2	S-3	S-4	S-5	R-1	R-2	R-3
Averag	2.5063	6.1085	1.0459	0.6703	-2.1473	-0.9399	7.1843	1.1605	1.4248
Max.	9.1866	7.6261	3.2777	5.3805	1.0273	7.1296	9.0739	4.2254	4.2593
Min.	-5.4832	2.1646	-2.1782	-6.4647	-6.0373	-5.2495	4.2790	-1.0590	1.0028
Range	14.669	5.4615	5.4559	11.845	7.0647	12.379	4.7949	5.2844	3.2565
S.D.	5.3780	1.3432	1.4634	4.0588	1.8036	3.4100	1.4183	1.6354	1.1384

relatively sudden increase in the sea surface height. According to these tendencies, both the ranges of the change and the standard deviation are larger than the other one's as shown in Table 3 (shaded cells are referred to these exceptional values in the table).

The results obtained for the event occurred on March 28, 2005 are shown in Fig. 6 and Table 4. The sea surface height anomaly decreases from March 26th 2005 to March 31st 2005 the area referred to hypocenter (solid line) although there are few significant changes about another reference grids. Large range and standard deviation are also appeared in Table 4 like the event on December 26th, 2004.

In both two results, it was identified that sea surface height anomaly suddenly changes before tsunami events. But the trend of the change is not same about these two events; sea surface height anomaly increased in hypocenter area before tsunami strike for the event on December 26th, 2004, but the anomaly decreased before the event on March 28th 2005. Most of tsunami is occurred by earthquake in the area where the oceanic plate sinks under the continental plate and one of the reasons for the sea surface height change is change in the ocean bottom topography. Therefore there is a possibility that both the increase and decrease in sea surface height are reflecting the upheaval and subsidence of ocean bottom, respectively. Since both of them might generate tsunami and change sea surface height, the satellite altimetry has a possibility to be useful tool of tsunami prediction. However the time lag between change in the bottom topography and sea surface height have to be considered to make this assumption sure,

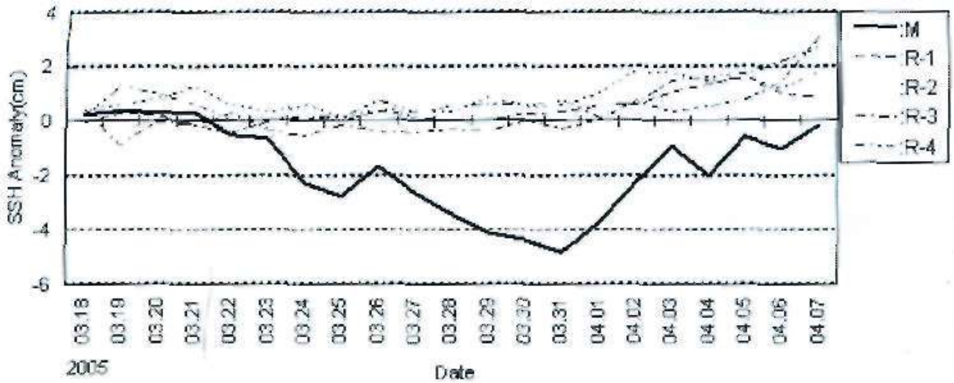

Fig. 6. As in Fig. 5, but for the tsunami occurred on March 28th, 2005

rable 4. As in Table 3, but for the event *m* March 28th, 2005

Stn. No.	M	R-1	R-2	R-3	R-4
Average	1.7610	0.3838	0.8724	0.3449	0.6593
Max.	0.3654	1.6070	1.8374	2.6583	3.0242
Min.	4.8298	0.4489	0.1256	0.8832	0.0095
Range	,5.1952	2.0559	1.7119	3.5415	3.0337
S.D.	1.6736	0.5245	0.5497	0.9926	0.6656

the sudden change in sea surface height anomaly begins one day before the tsunami in both cases. This means that the time lag between them is reasonable from a view point of the mechanism in reflection of change in bottom topography by earthquake as a first approximation. Thus the results obtained from the analysis of the change in sea surface height suggest that possibility of tsunami detection at least one day before tsunami occurrence, even though the mechanism of generation of tsunami can not be explained dynamically. And also, it is necessary to analyze the more satellite altimeter data that can detect the SSHA before occurrences of Tsunami statically.

Conclusions

Change in sea surface height anomaly was analyzed and the discovery of tsunami symptom was made a trial by satellite altimeter data in this study. As a result of that it is found that the sea surface height anomaly changes one day before tsunami occurrence in hypocenter and some of aftershock areas. This trend was identified by the comparison between the change in sea surface anomaly in the area referred to hypocenter, aftershock, and reference area defined as one degree grid in satellite altimetry. Time scale of sea surface height anomaly showed the significant change in the anomaly before tsunami event and the statistical results suggested remarkable change of the anomaly derived from the range and standard deviation of sea surface height anomaly in the grid settled **on** hypocenter and aftershock areas. The possibility of this method and trial as a tool for development in tsunami warning system was shown with reasonable quantitative basis. The necessary time for the evacuation from tsunami depends on the scale of shelter; (1) one hour for emergency shelter, (2) five hours for schematic or organized avoidance, and (3) ten hours for escape with the property. In this study, it is suggested that the symptom might be detected in change in sea surface height anomaly one day before the tsunami event by application of satellite altimetry and its advantage and usefulness with the comparison between conventional methods and concepts. But the results obtained here is just an application to the two tsunami event occurred in close time and spatial scale. Further analysis is necessary about another location and period to check the capability and possibility of this method in wide range of both spatial and time scale.

This method can be utilized for the development of disaster prevention system from a viewpoint of actual avoidance of Bunami disaster in wide spatial coverage and enough periods for the preparedness.

Acknowledgement

Most of satellite altimeter data were supported and supplied by the Colorado Center for Astrodynamics Research (CCAR), University of Colorado, Boulder. USA. The authors express special thanks for iheir assistance passing through both personal communications and web archive system. This study was partially supported by Japan Aerospace Exploration Agency (JAXA).

References

Arbic. B. K-, S. T. Garner, R. W. Hallberg, and H. L. Simmons. 2004. The accuracy of surface elevations in forward global barolropic and baroclinic tide models. Deep-Sea Research II, 51:3069-3101.

Lemoine, F. G.. S. C. Kenyon, J. K. Factor. R. G. Trimmer, N. K. Pavlis, D. S. China, C. M. Cox, S. M. Klosko, S. B. Luthcke. M. H. Torrcnce, Y. M. Wang, R. G. Williamson, E. C. Pavlis, R. H. Rapp and T. R. Olson. 1998. The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NlMA) Geopotential Model EGM96, NASA/TP-1998-206861. 575p.

Liang. C.-K. 1983. The Adjustment and Combination of Gcos-3 and Seasat Altimeter data. Dcpt. of Geod. Sci., Ohio Stale Univ. Rep.. 346:1-68.

Morel, L. and P. Willis. 1999. Systematic effects of terrestrial reference frames on mean sea level determinations. Poster presented at TOPEX/Poseidon, JASON-1 SWT meeting. Saint Raphael, Oct. 25-27.

Naeijc, M. E. Doombos. L. Mathers, R. Scharroo, E. Schrama. and P. Visscr. 2002. Radar Altimeter Database System: Exploitation and Extension (RADSxx), Final Report NUSP-2 report 02-06. NUSP-2 project 6.3/IS-66. Space Research Organisation Netherlands (SRON), Utrecht, the Netherlands.

Ncrcm, R. S., B. J. Haines, J. Hendricks. J. F. Minster, G. T. Mitchum and W. B. White. 1997. Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data" Geophysical Research Letters. 24:1331-1334.

Rapp, R. H. 1985. Detailed Gravity Anomalies and Sea Surface Heights Derived From Geos-3/Scasat Altimeter Data. Dep. of Geod. Sci.. Ohio State Univ., Rep. 365-

Rowlands, D. 1981. The Adjustment of Seasat Altimeter Data on a Global Basis for Gcoid and Sea Surface Height Determinations. Dep. of Geod. Sci., Ohio State Univ., Rep. 325.

Sandwcll, D. T. 1984. A Detailed View of the South Pacific Geoid From Satellite Altimetry. J. Geophys. Res., 89:1089-1104.

Sandwell, D. T. and W. H. F. Smith. 997. Marine gravity anomaly from Geosat and ERS-I satellite altimetry. J. Geophys. Res., 102:10039-10054.

Titov, V. V., F. I. Gonzalez, E. N. Bernard, M. C. Eblc, H. O. Motjeld, J. C. Newman, and A. J.Venturato. 2005. Real-time tsunami forecasting: Challenges and solutions. Natural Hazards, 35(l):41-58.

Wahr, J. and M. Molenaar. 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. J-Gcophys. Res., 103:30205-30229.