Observation and Modeling of the January 2009 West Papua, Indonesia Tsunami

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Abstract—We modeled a tsunami from the West Papua, Indonesia earthquakes on January 3, 2009 ($M_w = 7.7$). After the first earthquake, tsunami alerts were issued in Indonesia and Japan. The tsunami was recorded at many stations located in and around the Pacific Ocean. In particular, at Kushimoto on Kii Peninsula, the maximum amplitude was 43 cm, larger than that at Manokwari on New Guinea Island, near the epicenter. The tsunami was recorded on near-shore wave gauges, offshore GPS sensors and deep-sea bottom pressure sensors. We have collected more than 150 records and used 72 stations' data with clear tsunami signals for the tsunami source modeling. We assumed two fault models (single fault and five subfaults) which are located to cover the aftershock area. The estimated average slip on the single fault model (80×40 km) is 0.64 m, which yields a seismic moment of 1.02×10^{20} Nm ($M_w = 7.3$). The observed tsunami waveforms at most stations are well explained by this model.

Key words: West Papua, Indonesia 2009 earthquake, tide gauge, wave gauge, GPS buoy, ocean bottom tsunami sensor, tsunami simulation.

1. Introduction

A large earthquake occurred on the north coast of Doberai Peninsula, West Papua, Indonesia (0.408°S , 132.886°E , $M_w = 7.7$ at 19:43:50 UTC according to USGS) on January 3, 2009. This earthquake was followed by the second event (0.707°S , 133.361°E , $M_w = 7.4$ at 22:33:40 UTC, according to USGS) 3 h later at about 60 km southeast. Focal mechanisms of thrust type by USGS's CMT solutions and the shallow depth of about 20 km indicate that these events

occurred on the plate boundary along the Manokwari Trench (e.g. OKAL, 1999) where the Pacific Plate is subducting beneath the Australian Plate (Fig. 1).

After the first event, Meteorological, Climatological and Geophysical Agency, Indonesia (BMKG) issued an alert for a local tsunami potential near the source region. According to the field survey of the coastal area, northern West Papua, near the sources (MUHARI *et al.*, 2009), the run-up heights were up to 1.97 m. The tsunami did not cause much damage to houses or fisheries facilities, and there were no casualties.

Far from the West Papua coast, the Japan Meteorological Agency (JMA) issued a Tsunami Advisory to the Izu-Bonin Islands, the southwestern coasts of Honshu and Shikoku Islands facing to Pacific Ocean, eastern coast of Kyushu Island, and Satsunan Islands (Fig. 2). The observed tsunamis at tide gauges along the Japanese coast range from a few to several tens of centimeters. The maximum tsunami amplitude of 43 cm was recorded at Kushimoto.

Around New Guinea Island, many earthquakes have occurred in the past. The earthquakes in 1996, 1998, September and October 2002, which generated tsunamis are noted with their labels in Fig. 1. The 1996, 2002 September and October tsunamis reached coasts in Japan, and were observed at some tide gauges. For the 1996 and September 2002 events, maximum tsunami heights of 1.04 m at Chichijima and 0.20 m at Naze were recorded, respectively (JMA, 2002, 2009).

The 2009 tsunamis were recorded not only at highly dense coastal tide gauges and near shore wave gauges but also at GPS buoys and ocean bottom tsunami sensors (OBTS) recently installed. For example, JMA's OBTS system in Tonankai was just started in November 2008 to monitor oceanographic phenomena such as tides, wind waves or tsunamis.

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In this paper, we describe the observed tsunami heights and waveforms, and model the tsunami to estimate the tsunami source using those data.

Figure 1

Epicenters of the January 2009 West Papua, Indonesia earthquakes (black star first event, white star second event). Gray circles indicate the previous earthquakes whose magnitudes are greater than seven, of which the events with labels are tsunamigenic earthquakes

Figure 2

Coastal areas of Japan, where tsunami advisories were issued by JMA for the January 2009 West Papua, Indonesia earthquakes

2. Observed Tsunamis

Tsunamis from the 2009 West Papua, Indonesia earthquakes were recorded on many coastal tide gauges in and around the Pacific Ocean (Fig. 3), as well as near-shore wave gauges, off-shore GPS buoys, and cabled OBTS (pressure gauges) off the Japanese coasts (Fig. 4). We have collected 105 tide gauge waveforms including tsunami signals from Indonesia's National Coordination Agency for Surveys and Mapping (BAKOSURTANAL), JMA, Japan Coastal Guard (JCG), Japan's Geographical Survey Institute (GSI), and USA's West Coast/Alaska Tsunami Warning Center (WCATWC). The tsunamis were also recorded at 29 near-shore wave gauges and eight offshore GPS buoys operated by Japan's Nationwide Ocean Wave information network for Ports and HarbourS (NOW-PHAS). Tsunami sensors installed on the ocean bottom by JMA and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 11 sensors in total (Boso 1, one of JMA's OBTS, malfunctioned), successfully recorded tsunami signals as well as seismic signals. Among these data, we selected 50 tide gauges, 10 wave gauges, 3 GPS buoys and 9 OBTS, which clearly recorded tsunami signals to be used for tsunami modeling. The locations of these selected stations, 72 in total, are listed in Table 1.

Figures 3b and 4b show the maximum tsunami heights (positive values of zero-to-peak in tsunami waveforms after the data processing which will be described later) at the observation stations. The tsunami heights are larger along the Izu-Bonin ridge system and the southern coasts of Japan, because of the waveguide effect (trapped wave energy in shallow ridge region) as pointed out by SATAKE and KANAMORI (1991) and SATAKE *et al.* (1992).

The tide gauge, wave gauge, GPS buoy and OBTS records usually include low frequency ocean tides and high frequency waves such as seismic waves or wind waves. We filter these records to retrieve the tsunami signals in the following way. First, we approximate the tidal component as a polynomial function, and remove the tides from the original records. Then, we apply a moving average with a box-car function which has a band width of three sampling points to reduce the high frequency noises. Figure 5 shows the processed records as examples of

Figure 3

a Locations of stations which recorded the 2009 West Papua, Indonesia tsunami, overlaid on the distribution of the simulated maximum tsunami height. *Triangles, squares, inverted triangles and diamonds* indicate the tide gauges, ocean bottom tsunami sensors (*OBTS*), wave gauges (*WG*) and GPS buoys, respectively. Epicenter of the first event (*black star*) is also shown. **b** Maximum heights (absolute values of zero-to-peak or zero-to-trough) of the observed tsunamis. *Rectangular* shows the computation area for tsunami simulations

a wave gauge at Shionomisaki, a GPS buoy off Mie Owase, and an OBTS of MPG2 off Shikoku (see Fig. 4a for the locations).

The observed tsunami waveforms indicate that the tsunami amplitudes range from a few to 40 cm at the tide gauges, a few to 10 cm at the wave gauges, up to

Figure 4

a Same as Fig. 3a, but for the region around Japan. The sources of the 2009 West Papua, Indonesia earthquakes are far south of this map (see Fig. 3a). **b** Same as Fig. 2b, but for the region around Japan

Table 1

List of tide gauges, wave gauges, GPS buoys and OBTS

Station*	Latitude (deg:min:s)	Longitude (deg:min:s)	Water depth (m)	Record sampling	MTH (m)**	Agencies***
Manokwari	0:51:25S	134:04:38E		1 min	0.32	BAKO
Biak	1:10:40S	136:03:21E		3 min	0.19	BAKO
Jayapura	2:32:42S	140:42:46E		1 min	0.088	BAKO
Yap	9:18:18N	138:04:37E		1 min	0.014	UH
Saipan	15:13:36N	145:44:31E		1 min	0.083	UH
Chichijima	27:06N	142:12E		15 s	0.36	JMA
Hachijojima	33:07:36N	139:48:28E		30 s	0.094	JCG
Miyakejima	34:03N	139:33E		15 s	0.22	JMA
Kozushima	34:12:18N	139:08:12E		30 s	0.23	JCG
Soma	37:50N	140:58E		30 s	0.094	GSJ
Katsuura	35:08N	140:15E		30 s	0.12	GSJ
Mera	34:55N	139:50E		15 s	0.28	JMA
Boso 2 (OBTS)	34:44:57N	140:45:29E	2,098	1 s	0.0087	JMA
Boso 3 (OBTS)	34:47:58N	140:30:42E	1,912	1 s	0.012	JMA
Yokosuka	35:17:05N	139:39:17E		30 s	0.084	JCG
Aburatsubo	35:10N	139:37E		30 s	0.25	GSJ
HPG1 (OBTS)	35:00:11N	139:13:29E	1,176	1 s	0.017	JAMS
Ito	34:53N	139:08E		30 s	0.043	GSJ
Shimoda	34:41N	138:58E		0.5 s	0.30	NAW
Shimoda (WG)	34:38:48N	138:57:11E	51.1	0.5 s	0.12	NAW
Irozaki	34:37N	138:51E		15 s	0.092	JMA
Tago	34:48N	138:46E		30 s	0.035	GSJ
Uchiura	35:01N	138:53E		15 s	0.098	JMA
Shimizuminato	35:01N	138:31E		15 s	0.044	JMA
Yaizu	34:52N	138:20E		30 s	0.13	GSJ
Omaezaki (WG)	34:37:17N	138:15:33E	22.8	0.5 s	0.045	NAW
Tokai (OBTS)	33:45:54N	137:35:23E	2,202	1 s	0.013	JMA
Tonankai 1 (OBTS)	33:39:15N	136:50:26E	2,050	1 s	0.0079	JMA
Tonankai 2 (OBTS)	33:51:28N	137:21:34E	1,120	1 s	0.013	JMA
Tonankai 3 (OBTS)	34:13:02N	137:41:31E	1,103	1 s	0.0098	JMA
Maisaka	34:41N	137:37E		15 s	0.060	JMA
Owase	34:05N	136:12E		15 s	0.20	JMA
Kumano	33:56N	136:10E		15 s	0.32	JMA
Mie owase (GPS)	33:54:08N	136:15:34E	210	1 s	0.049	NAW
Uragami	33:34N	135:54E		15 s	0.23	JMA
Kushimoto	33:29N	135:46E		15 s	0.43	JMA
Shionomisaki (WG)	33:25:59N	135:44:50E	54.7	0.5 s	0.044	NAW
Shirahama	33:41N	135:23E		15 s	0.13	JMA
Gobo	33:51N	135:10E		15 s	0.23	JMA
Wakayama	34:13N	135:09E		15 s	0.067	JMA
Wakayama SW (GPS)	33:38:32N	135:09:24E	201	1 s	0.033	NAW
Komatsushima	34:01N	134:35E		15 s	0.097	JMA
Awayuki	33:46N	134:36E		15 s	0.32	JMA
Murotomisaki	33:16N	134:10E		15 s	0.24	JMA
MPG1 (OBTS)	32:23:27N	134:28:31E	2,308	1 s	0.0095	JAMS
MPG2 (OBTS)	32:38:35N	134:21:53E	1,507	1 s	0.013	JAMS
Kochi	33:30N	133:34E		15 s	0.12	JMA
Kochi (WG)	33:28:57N	133:35:13E	24.1	0.5 s	0.071	NAW
Susaki	33:23N	133:18E		0.5 s	0.22	NAW
Kure	33:20N	133:15E		30 s	0.16	GSJ
Kamikawaguchi (WG)	33:01:54N	133:03:29E	27.9	0.5 s	0.10	NAW
Tosashimizu	32:47N	132:58E		15 s	0.20	JMA
Kochi W (GPS)	32:37:52N	133:09:21E	309	1 s	0.064	NAW
Hosojima	32:26N	131:40E		30 s	0.14	GSJ
Hosojima (WG)	32:26:36N	131:43:42E	48.3	0.5 s	0.040	NAW

Table 1 continued

Station*	Latitude (deg:min:s)	Longitude (deg:min:s)	Water depth (m)	Record sampling	MTH (m)**	Agencies***
Aburatsu	31:35N	131:25E		15 s	0.21	JMA
Shibushi	31:29N	131:07E		0.5 s	0.16	NAW
Odomari	31:01:12N	130:41:29E		30 s	0.26	JCG
Nishinoomote	30:43:53N	130:59:40E		30 s	0.21	JCG
Tanegashima	30:28N	130:58E		15 s	0.33	JMA
Naze (WG)	28:27:07N	129:31:18E	54.6	0.5 s	0.031	NAW
Amami	28:19N	129:32E		15 s	0.24	JMA
Nakagusu	26:20N	127:50E		0.5 s	0.11	NAW
Nakagusu (WG)	26:14:32N	127:57:55E	39.6	0.5 s	0.052	NAW
Okinawa	26:11N	127:49E		30 s	0.10	GSI
Naha	26:13N	127:40E		15 s	0.085	JMA
Naha (WG)	26:15:28N	127:38:52E	51.0	0.5 s	0.033	NAW
Taira	24:49N	125:17E		0.5 s	0.11	NAW
Ishigaki	24:20N	124:10E		15 s	0.080	JMA
Ishigakioki (WG)	24:21:55N	124:06:10E	34.8	0.5 s	0.036	NAW
Yonaguni	24:27N	122:57E		15 s	0.037	JMA
Minamidaitojima	25:52N	131:14E		15 s	0.039	JMA

Values written in bold are from JMA (2009), the others are read in this study

WG wave gauge, GPS GPS buoy, OBTS ocean bottom tsunami sensor, JMA Japan Meteorological Agency, UH University of Hawaii, Sea Level Center, BAKO National Coordination Agency for Surveys and Mapping, Indonesia (BAKOSURTANAL), JCG Japan coastal guard, GSI Geographical Survey Institute, NAW Nationwide Ocean Wave information network for Ports and HARbourS (NOWPHAS), JAMS Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

* Station names with the sensor types in parentheses. Tide gauges are listed without parentheses

** Maximum tsunami height (positive value of zero-to-peak of the observed tsunami waveform)

*** Agencies or networks which are responsible for the tsunami waveforms data

Figure 5

Tsunamis recorded on near-shore wave gauge (*left*), offshore GPS buoy (*middle*) and ocean bottom tsunami sensor (*right*). At each station (the locations are shown in Fig. 4a) the upper trace shows the de-tided records including short-period components, and the *bottom traces* are the tsunami signals by filtering out the short-period components

5 cm at the GPS buoys, and up to 1.5 cm at the OBTS, respectively. These differences of the tsunami amplitude are basically due to the differences in water depth at the observation point. The tide gauges are installed along coastal areas at depths of a few to several meters, wave gauges at depths of about 10 to

50 m, GPS buoys at depths of about 200 m, and OBTS at depths of about 1,000–4,000 m. The tsunami with maximum amplitude of 36 cm was observed at Chichijima located on Izu-Bonin ridge, which is comparable to that observed at Manokwari, the nearest tide gauge to the sources.

Figure 6

Slip distributions estimated by tsunami waveform inversions adopting different fault models (**a** single fault, **b** five subfaults) with subfault numbers. *Black star* shows the mainshock epicenter. *Circles in black* indicate aftershocks within about 3 h after the mainshock (before the second event). The second event and following aftershocks within 1 day after that event are also shown in *gray symbols*

3. Tsunami Modeling

3.1. Bathymetry Data

Since phase velocities of shallow-water (tsunami) waves depend on water depth, accurate bathymetric data are essential for tsunami numerical computations. For the global ocean, a gridded bathymetry dataset is available from GEBCO (British Oceanographic Data Centre, 1997). The GEBCO data was newly updated with 30 arc-second grid resolution (GEBCO_08). We use this bathymetry data for calculating tsunami waveforms or Green functions.

3.2. Fault Models

We first assume a single fault for the first event and estimate the average slip on the fault. Then, in order to estimate the extent of the tsunami source and its slip distribution, we divide the tsunami source into five subfaults to cover the area of aftershocks that occurred during 3 h after the first event but before the second event (Fig. 6). A fault model for the second event is not considered, because the tsunami from the second event overlapped with the later phases of the first event's tsunami, which made it difficult to distinguish the arrival of the second event's tsunami from the observed records.

We perform two sets of inversion to estimate the tsunami source using the single fault model and five-

Table 2

Slip distributions estimated by tsunami waveform inversions with different fault models

No.	Latitude (°S)	Longitude (°E)	Slip and error (m)	
			Single fault	Five subfaults
1	0.15	132.6	—	0.00 ± 0.14
2	0.21777	132.76661	0.64 ± 0.32	0.00 ± 0.00
3	0.28553	132.93323		0.70 ± 0.34
4	0.35330	133.09984		0.00 ± 0.17
5	0.42106	133.26597		2.07 ± 1.10

Location (latitude and longitude) indicates the northwest corner of each fault or subfault

subfault model. The size of the fault is 80×40 km for the single fault model. For the five subfault model, each subfault is 20×40 km (Fig. 6 and Table 2). The focal mechanism of strike 112° , dip 36° , slip angle 77° , from the USGS CMT solution of the first event, and the top depths of 10 km, are adopted for all the fault models. We assume an instantaneous rupture for the two fault models, because the tsunami propagation velocity is 0.1 km/s for the water depth of 1,000 m, much smaller than the typical rupture velocity of a few km/s. The epicenter is located between subfaults 2 and 3.

3.3. Finite-Difference Computation

In order to calculate tsunami propagation from each fault to the stations, the linear shallow-water, or

long-wave, equations were numerically solved by using a finite-difference method (SATAKE, 1995). Details of the governing equations without Coriolis force are described in FUJII and SATAKE (2007). The computation area extends from 120°E to 155°E and 5°S to 45°N (rectangular area in Fig. 3a. The bathymetric grid interval is uniformly 30'' (30 arc-seconds, about 0.9 km), hence there are $4,200 \times 6,000$ grid points along the longitude and latitude directions, respectively. We set a minimum water depth on the coasts to 2 m. Because the observed tsunami heights of the West Papua tsunami were mostly up to a few tens of centimeters at the tide gauges, the small amplitude assumption in linear shallow-water long-wave equations is valid. We made the computations of 9 h for tsunami propagation. A time step of 1 s is used to satisfy the stability condition for the finite-difference method.

As an initial condition for the tsunami numerical computation, static deformation of the seafloor is calculated for a rectangular fault model (OKADA, 1985) and used assuming that the initial water height distribution is the same as that of seafloor. We also consider the effects of coseismic horizontal displacement in regions of steep bathymetric slope (TANIOKA and SATAKE, 1996). We assumed a constant rise time (or slip duration) of 30 s for the single fault model and each subfault. Waveforms at the observed stations were computed and used as Green functions for the inversion.

3.4. Tsunami Waveform Inversions

We used the non-negative least square method (LAWSON and HANSON, 1974) and delete-half jackknife method (TICHELAAAR and RUFF, 1989) to estimate slips and errors, respectively. The observed tsunami waveforms were resampled at 1 min intervals, hence synthetic waveforms are also computed at 1 min interval. We used the first cycles of the tsunami waveforms for the inversions, because the limited resolution of bathymetry data near coastal tide gauges and near-shore wave gauges may prevent accurate modeling of later phases such as reflected waves. The total number of data points used for the inversions is 641. We weight the OBTS data ten times, GPS buoy data five times, and wave gauge data three times greater than the other tide gauge data, because the amplitudes

of near-shore or offshore records are smaller, by an order of magnitude as described in Sect. 2, than those of tide gauge records.

4. Results and Discussions

The inversion results are shown in Table 2 and Fig. 6. The estimated slip on the single fault model (Fig. 6a) is 0.64 m, which yields a seismic moment of 1.02×10^{20} Nm ($M_w = 7.3$) assuming a rigidity of 5.0×10^{10} N/m². For the five-subfault model (Fig. 6b), a moderate slip of 0.70 m was estimated near the epicenter (subfault 3) and a large slip of 2.07 m was located on the eastern end of the source (subfault 5). The amount of largest slips at the eastern end of the source region in the five-subfault models may not be well resolved because of the large error (1.10 m; see Table 2). The total seismic moment is calculated as 1.11×10^{20} Nm ($M_w = 7.3$) for the five-subfault model, assuming the same rigidities of 5.0×10^{10} N/m² for all the subfaults. Regardless of the fault models, the estimated moment magnitude is smaller than that inferred from seismic data (cf. $M_w = 7.6$ from USGS CMT solution). Before the inversions, we performed a forward modeling referring the source model of $M_w = 7.6$ and found that the first-wave amplitudes of synthetic waveforms at some stations of OBTS (off Tokai, Tonankai and Shikoku) were overestimated for the observed amplitudes. Since the Green functions of such OBTS installed in deep sea, which were used for the inversions, must be calculated more accurately than the ones of tide gauges or wave gauges located near coasts, the moment magnitude of 7.6 might be slightly overestimated for the tsunami generation. The source process of the 2009 West Papua earthquake has been inferred from teleseismic body waves by HAYES (2009) and POIATA *et al.* (2010). Their results show a single asperity around the epicenter. The large slip on subfault 3 in the five-subfault model may correspond to their single asperities.

Comparison of the observed tsunami waveforms and the synthetic ones from the single fault model is shown in Fig. 7. The calculated tsunami waveforms from the five-subfault model are not shown, because the differences in synthetic waveforms from the two

Figure 7

a Comparisons of the observed (gray lines) and synthetic (black lines) tsunami waveforms computed from the estimated slip by adopting the single model. Time ranges shown by solid curves are used for the inversions; the dashed parts are not used for the inversions, but shown for comparison. Out of 36 waveforms shown here, we used parts of 13 records (underlined stations) for the inversions. **b** (cont'd) Out of 36 waveforms shown here, we used parts of 13 records (underlined stations) for the inversions. (Submitted January 3, 2010, Revised June 15, 2010, Accepted July 1, 2010)

fault models are much smaller than the differences between the observed and synthetic waveforms. We used most of the observed tsunami waveforms at wave gauges, GPS buoys, and OBTS around Japan for the inversions. On the other hand, we used the observed tsunami waveforms at five tide gauges on

the small islands (Biak, Yap, Saipan, Chichijima, Minamidaitojima) which are located on the tsunami's way from the source to the offshore or near-shore stations of the Japanese main islands. Some stations' data were not used for the inversions, because the first arrivals of the observed waveforms do not match the

Figure 7
continued

synthetic ones (e.g. Manokwari, Jayapura, HPG1 (OBTS)), although the tide gauges are located close to the source. The synthetic waveforms generally agree with the observed phases at most stations, however, the calculated tsunami amplitudes are consistently underestimated. At some stations (e.g. Biak, Saipan, Shimoda (WG)), the synthetic

waveforms are well reproduced not only for the first cycles of tsunami waveforms (inversion time windows) but also for the later phases which were not used in the inversions. It is difficult to judge which of the single fault and five-subfault model is the best model, because the differences of the synthetic waveforms among the both fault models are very

small. This may indicate the limitation due to the poor station coverage to resolve the extent of the tsunami source; in this case we mainly used far field data located in the direction perpendicular to the fault strike.

5. Conclusions

The tsunamis generated by the January 2009 West Papua, Indonesia earthquakes were recorded not only at many coastal tide gauges located in and around the Pacific Ocean but also at near-shore wave gauges, off-shore GPS buoys and OBTS off the Japanese coasts. Using the observed tsunami waveforms, we modeled the tsunami from the first event to estimate the tsunami source and found that the tsunami data observed at tide gauges, wave gauges, GPS buoys and OBTS were well reproduced. The recently updated bathymetry data of GEBCO_08, 30 arc-second grid data was used in the tsunami simulations. The average slip of 0.64 m was estimated on the single fault of 80×40 km. The calculated seismic moment is 1.01×10^{20} Nm ($M_w = 7.3$), slightly less than the magnitude inferred from seismic data ($M_w = 7.7$).

Acknowledgments

We thank the National Coordination Agency for Surveys and Mapping (BAKOSURTANAL), Japan Coastal Guard (JCG), Geographical Survey Institute (GSI), and West Coast/Alaska Tsunami Warning Center (WCATWC) for providing us tide gauge data. We also thank Ports and Harbors Bureau (PHB) under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and Port and Airport Research Institute (PARI) for providing us with tide gauge, wave gauge and GPS buoy data. The data of ocean bottom tsunami sensors of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) were downloaded from their web site. We thank Efim Pelinovsky and an anonymous reviewer for their valuable comments which have improved our manuscript. Most of the figures were generated using the Generic Mapping Tools (WESSEL AND SMITH, 1998).

This research was partially supported by Grants-in-Aid for Scientific Research (B) (No. 21310113), Ministry of Education, Culture, Sports, Science and Technology (MEXT), and Science and Technology Research Partnership for Sustainable Development (SATREPS) from Japan Science and Technology Agency (JST), Japan International Cooperation Agency (JICA), State Ministry of Research and Technology of Indonesia (RISTEK) and Indonesian Institute of Science (LIPI).

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(Received January 3, 2010, revised June 15, 2010, accepted July 1, 2010, Published online December 14, 2010)