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Re-estimation of tsunami source of the 1952 Tokachi-oki earthquake

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Previous studies indicate that the source area of the 2003 Tokachi-oki earthquake (M 8.0) was smaller than the comparable 1952 Tokachi-oki earthquake (M 8.2) source. We reinverted the 1952 tsunami waveforms, by adopting higher-resolution tsunami simulation method, and estimating and correcting for clock errors of tide gauges from comparison of the 1952 and 2003 tsunami waveforms. The estimated slip distribution indicates that the 1952 tsunami source area was indeed larger than the 2003 source. The distributions of measured and computed coastal tsunami heights also support this conclusion.
Key words: Tokachi-oki earthquake, tsunami, tide gauge, Kuril trench.

1. Introduction

The southern Kuril trench, where the Pacific plate subducts beneath Hokkaido at a rate of ∼8 cm/yr, has a history of recurring large earthquakes and tsunamis (Fig. 1). In the Tokachi-oki region, at the southwestern end of the Kuril trench, earthquakes have been documented in 1843 (M 8.0) and 1952 (M 8.2). In the Nemuro-oki region, to the east, large earthquakes occurred in 1894 (M 8.2) and in 1973 (M 7.8).

In March 2003, the Japanese government released long-term forecast of earthquakes along the Kuril trench (Earthquake Research Committee, 2004). They estimated that the probability of large (M ∼ 8) earthquakes in the next 30 years (starting March 2003) would be 60% in Tokachi-oki and 20–30% in Nemuro-oki. The forecast was based on the past recurrence of large earthquakes. The boundary between Tokachi-oki and Nemuro-oki was drawn from the slip distribution of the 1952 Tokachi-oki earthquake (Hirata *et al.*, 2003).

A large (M 8.0) earthquake occurred in Tokachi-oki on September 26 (JST), 2003. The source region, estimated from seismic waves (e.g., Yamanaka and Kikuchi, 2003), aftershock distribution (Hamada and Suzuki, 2004) and tsunami first arrivals (Hirata *et al.*, 2004), was smaller than that of the 1952 Tokachi-oki earthquake and forecasted area (Fig. 1). Tanioka *et al.* (2004a) made an inversion of the 2003 tsunami waveforms and showed that the slip distribution on the fault is significantly different from that of the 1952 Tokachi-oki earthquake, which was also estimated from tsunami waveform inversion by Hirata *et al.* (2003).

In this paper, we reanalyze the 1952 tsunami waveform data. The two inversion results, 1952 Tokachi-oki (Hirata *et al.*, 2003) and 2003 Tokachi-oki (Tanioka *et al.*, 2004a), are not directly comparable, because of different resolution of tsunami simulation and different subfault size. In addition, timing accuracy of tide gauge records is different in 1952 and 2003. We first compare the tide gauge records from the two events, estimate and correct for the clock errors of 1952, compute tsunami waveforms using fine grids similar to those of Tanioka *et al.* (2004a), and re-perform the waveform inversion.

2. Tide Gauge Records

The 1952 tsunami waveform was recorded at 13 tide gauge stations in Hokkaido and northern Honshu (Fig. 1). Among them, seven stations also recorded the 2003 tsunami. We first compare the waveforms recorded at the common stations (Fig. 2). The waveforms are in general very similar to each other. At Kushiro, the tide gauge did not follow the actual sea level change of the 1952 tsunami, because of floating ice (Central Meteorological Agency, 1953). Hence we followed Hirata *et al.* (2003) to use only the initial part of the waveform. At Hachinohe and Ayukawa, the 1952 amplitudes are larger than those of 2003, but the waveforms are similar. The tsunami arrival times are different for the 1952 and 2003 records. We shift the waveforms and align them at the first peak (Fig. 2). The time adjustments are up to 10 min. At Hachinohe, Ayukawa, and Choshi, the 1952 waveforms are delayed for 8 min, 5 min and 10 min, respectively, while at Kushiro and Miyako, the 1952 waveforms are advanced for 8 min and 5 min, respectively. The time shifts seem to be randomly distributed, without any systematic or regional tendency.

We assume that the above time shifts are due to the clock errors of the 1952 tide gauges, and apply the corrections to the observed waveforms. This is a reasonable assumption, because the 1952 tide gauges were recorded on paper drums, with a typical speed of 2 cm per hour, while the 2003 gauges were digitally recorded. If the 1952 and

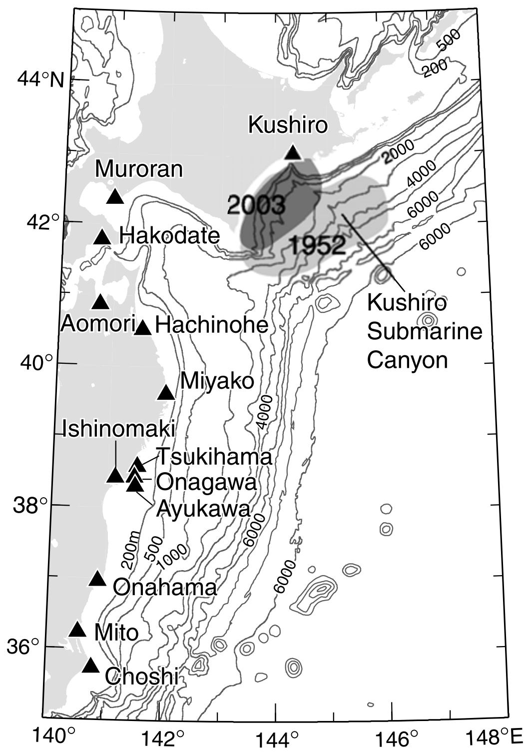

Fig. 1. Source regions of the 1952 and 2003 Tokachi-oki earthquakes (Hirata *et al*., 2003, 2004). Solid triangles show the tide gauge stations where the 1952 tsunami waveforms were recorded. Tsunami numerical simulation was made in the map region and bathymetry.

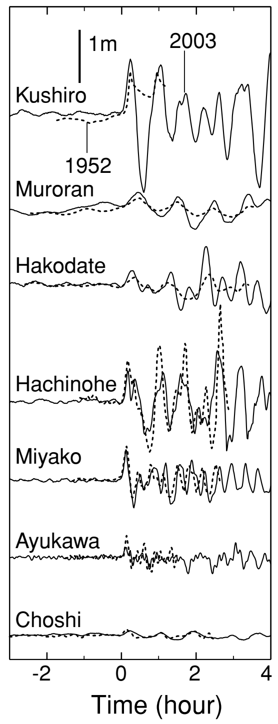

Fig. 2. Comparison of tsunami waveforms from the 1952 (dashed curves) and 2003 (solid curves) Tokachi-oki earthquakes. The origin of time axis is at the tsunami arrival time at each station. The 1952 waveforms are aligned to the 2003 waveforms at the first peak. The time shifts are as follows (positive means 1952 is advanced while negative is delayed). Kushiro: 8 min, Muroran: −1 min, Hakodate: 0 min, Hachinohe: −8 min, Miyako: 5 min, Ayukawa: −5 min, Choshi: −10 min.

2003 sources were the same, we expect the above correction would remove the clock error. If, on the other hand, the two sources are different, then the above correction may remove the source effect, as well as clock errors, and would also map the two sources in a similar location.

We test our assumption by examining the Kushiro tide gauge records. On the 2003 Kushiro record, the first arrival and first peak are at 16 min and 28 min after the earthquake, respectively. By aligning the 1952 and 2003 records at the first peak, we obtain the clock correction of 8 min (Fig. 2). The 1952 tide gauge record (on a copy of the original tide gauge record archived at the Earthquake Research Institute, University of Tokyo) shows a disturbance of water level caused by ground shaking at 10:29 AM (Japan Standard Time). Because the origin time of the 1952 Tokachi-oki earthquake was 10:22, this indicates that the actual clock delay was 7 min, very similar to what we estimated from the comparison with the 2003 record. Unfortunately, ground shaking was not recorded at any other tide gauge stations.

We have not corrected for tide gauge response to tsunamis. Satake *et al.* (1988) measured the tide gauge response to tsunamis and applied the corrections to the tsunami waveforms from the 1983 Japan Sea earthquake. At some stations, mostly on the Japan Sea coasts, intake pipes are narrow to filter out winter wind waves and the measured response was not very good for short period (<10 min) components of tsunamis. While we do not know the actual response of tide gauges in 1952, the observed periods are mostly 20 min or longer, hence we anticipate that the effect of tide gauge response is minimum except for Kushiro.

3. Tsunami Simulation and Inversion

We compute tsunami waveforms by using a finite-difference method for the linear long-wave momentum and continuity equations (e.g., Satake, 2002). The grid size is 30″ of the arc (about 925 m along the meridian) for deep ocean, and 6″ (about 185 m) near the six tide gauge stations (Kushiro, Hachinohe, Miyako, Tsukuhama, Onagawa and Ayukawa). Finer grid system is not adopted around the other tide gauge stations, because the records are characterized by longer period and smaller amplitude. The grid sizes are similar to those used by Tanioka *et al.* (2004a) for the 2003 Tokachi-oki earthquake tsunami (20″ for deep ocean and 4″ around tide gauge stations), but much smaller than 60″ (about 1850 m) used by Hirata *et al.* (2003) for the 1952 tsunami. We used bathymetry and topography in 1952; extensive breakwater has been constructed in Kushiro and Hachinohe since 1952 (Fig. 3). In Hachinohe area, the location of tide gauge station is different (Same for the 1952 tsunami and Minato for the 2003 tsunami). The time step for the finite-difference computation is set to 1.5 s to satisfy the stability condition.

Tsunami waveforms computed on different grids are often very different. At Miyako, Onagawa and Ayukawa, the arrival times become early by several minutes and the amplitudes become nearly double when the finer grid system is used (Fig. 4). Tsunami waveforms computed on even smaller grid size (as small as 75 m) indicates that no further improvement is obtained for tsunami waveforms in northern Honshu.

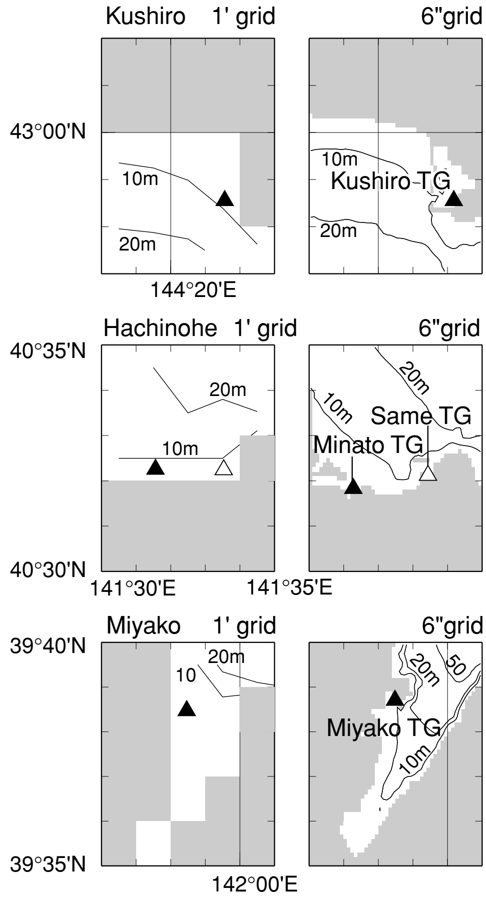

Fig. 3. Detailed topography and bathymetry around tide gauge stations at Kushiro, Hachinohe and Miyako. Gray color indicates land. Left column for 1′ grid (1850 m along meridian) and right column for 6″ grid (185 m).

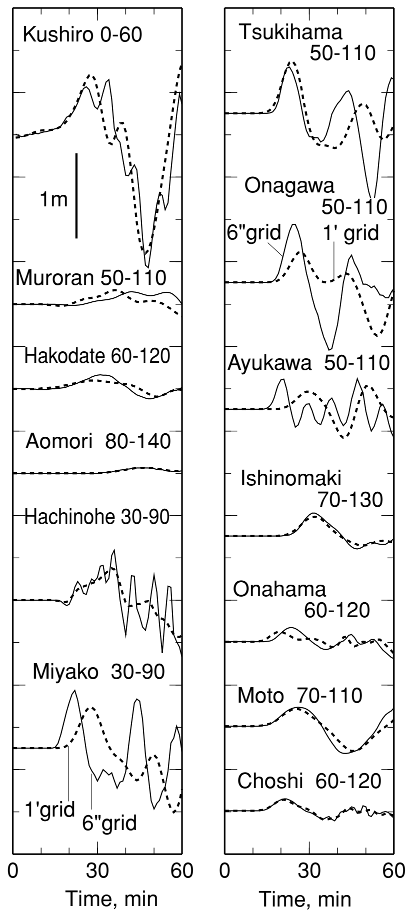

Fig. 4. Comparison of computed tsunami waveforms with different gird sizes. The dashed curves are computed on 1′ grid, while the solid curves are on finer grids (6″ for Kushiro, Hachinohe, Miyako, Tsukihama, Onagawa and Ayukawa, and 30″ for other stations), from the slip distribution of Hirata *et al.* (2003). The numbers next to the station names indicate the time window (in minutes from the earthquake origin time).

We divide the fault into smaller subfaults. Two sets of subfault systems, 10 block model and 18 block model, are used. The 10 block model has the same configuration as Hirata *et al.* (2003). The 18 block model is the same as Tanioka *et al.* (2004a) except that four additional faults with the same size (40 km $\times$ 40 km) are added at the southwestern end of the 2003 Tokachi-oki source. The fault parameters are compiled in Tables 1 and 2.

The slip amount on each subfault is then estimated by non-negative least-squares method. The error associated with the slip estimate is computed by the delete-half jackknife method, a resampling method in which inversion is repeated 100 times by randomly eliminating a half of the data points (waveforms) to estimate standard error (e.g., Tichlaar and Ruff, 1989).

4. Slip Distribution

We compare the slip distributions on the fault, both the 10 and 18 block models, with those from the previous models of the 1952 event (Hirata *et al.*, 2003) and the 2003 event (Tanioka *et al.*, 2004a) (Figs. 5 and 6). We also compute vertical deformation of seafloor, which is the actual source of tsunami.

For the 10 block model, the maximum slip is smaller than that of Hirata *et al.* (2003). The large slips estimated by Hirata *et al.* (2003) were on subfault E, a deeper part of Tokachi-oki, and subfaults F and I, located off Akkeshi. The slip amount on subfault E is similar (5.6 m in Hirata *et al.* becomes 4.6 m), but those on subfaults F and I become substantially smaller, from 4.2 to 2.8 m on subfault F and from 7.2 m to 2.8 m on subfault I. The seafloor deformation patterns are similar; two peaks near the trench axis off Akkeshi and deeper part of Tokachi-oki, although the amount and the locations are slightly different. The large subsidence area off Akkeshi computed from the Hirata *et al.* (2003) model disappears.

The observed and computed waveforms are very similar at most stations (Fig. 7). In addition to the case in which all the 12 stations are used, we also make two additional cases in which we use (1) only seven stations (Kushiro, Muroran, Hakodate, Hachinohe, Miyako, Ayukawa and Choshi) where the clock corrections was estimated and corrected; and (2) only six stations (Kushiro, Hachinohe, Miyako, Tsukihama, Ongawa and Ayukawa) where finest (6″) girds were employed for computing waveforms (Tables 1 and 2). As can be seen in the table, the estimated slips for the three cases agree within the range of estimation errors.

A careful inspection of Fig. 7 reveals that the computed

Table 1. Fault parameters and estimated slip distribution on the 10 block model.

									12 sta		7 sta		6 sta		4 sta		Hirata*	
No	length	width	strike	dip	rake	depth	lat	lon	slip	error	slip	error	slip	error	slip	error	slip	error
	km	km	deg	deg	deg	km	deg N	deg E	m	m	m	m	m	m	m	m	m	m
A	47	55	238	13	117	12.5	41.539	144.25	0.54	0.29	0.19	0.27	0.4	0.29	0	0.32	1.54	0.37
B	47	45	238	26	115	24.4	41.946	143.91	0.00	0.06	0	0.25	0	0.00	1.27	1.31	0	0.72
C	47	55	238	6	117	10.0	41.516	144.93	0.83	0.37	0.83	0.4	1.02	0.40	0.95	0.49	1.23	0.70
D	47	55	238	19	116	15.8	41.932	144.59	1.92	0.45	1.65	0.46	1.79	0.51	2.16	0.58	2.53	0.70
E	47	45	238	33	113	33.7	42.333	144.27	4.55	1.47	4.89	1.42	4.85	1.44	0.64	2	5.63	1.44
F	47	55	238	6	117	10.0	41.731	145.42	2.76	0.73	2.59	0.71	3.42	0.77	4.4	0.93	4.24	1.18
G	47	55	238	19	116	15.8	42.152	145.08	3.17	0.71	2.81	0.75	3.46	0.73	5.22	0.81	1.36	1.16
H	47	45	238	33	113	33.7	42.556	144.76	1.70	1.30	1.04	1.27	1.72	1.32	5.82	1.82	0	1.23
I	69	55	238	6	117	10.0	42.044	146.13	2.79	1.10	2.29	0.97	3.63	1.00	5.13	1.82	7.16	1.60
J	69	55	238	19	116	15.8	42.472	145.8	2.29	0.45	1.76	0.53	2.55	0.57	4.55	0.77	1.74	0.63

Depth, lat and lon are for the southeastern edge of each subfault. *After Hirata *et al.* (2003).

Table 2. Fault parameters and estimated slip distribution on the 18 block model.

									12 sta		7 sta		6 sta		4 sta		2003*	
No	length	width	strike	dip	rake	depth	lat	lon	slip	error	slip	error	slip	error	slip	error	slip	error
	km	km	deg	deg	deg	km	deg N	deg E	m	m	m	m	m	m	m	m	m	m
1	40	40	230	20	109	39	42.62	144.82	0.89	1.71	1.28	1.23	0.34	1.21	0.18	1.71	2.10	0.10
2	40	40	230	20	109	39	42.38	144.45	6.74	1.54	5.85	1.65	7.61	1.28	7.21	2.30	1.50	0.20
3	40	40	230	20	109	39	42.15	144.08	0.00	0.32	0.00	0.91	0.00	0.02	0.00	3.09	4.30	0.10
4	40	40	230	20	109	39	41.92	143.72	0.40	0.51	0.72	0.45	0.00	0.86	10.21	2.53	0.00	0.00
5	40	40	230	20	109	25	42.35	145.12	3.48	1.12	2.77	1.09	3.91	1.10	3.78	1.48	0.10	0.10
6	40	40	230	20	109	25	42.12	144.75	1.82	1.21	1.10	1.07	1.61	1.12	0.00	1.03	0.00	0.00
7	40	40	230	20	109	25	41.88	144.38	0.00	0.43	0.00	0.21	0.00	0.26	0.00	0.26	1.20	0.10
8	40	40	230	20	109	25	41.65	144.02	0.12	0.37	0.00	0.15	0.00	0.20	0.00	0.00	0.00	0.00
9	40	40	230	6	110	12	42.19	145.89	1.63	1.14	0.74	1.31	1.70	1.35	1.87	2.36	0.00	0.10
10	40	40	230	16	109	14	42.08	145.38	2.32	1.00	2.09	0.94	2.76	1.03	3.27	1.30	0.30	0.10
11	40	40	230	16	109	14	41.85	145.02	1.63	0.73	1.24	0.70	1.81	0.73	1.59	1.05	0.00	0.00
12	40	40	230	6	110	8	41.92	146.20	0.00	1.33	0.19	2.41	0.00	1.95	2.89	4.59	0.00	0.00
13	40	40	230	6	110	10	41.82	145.70	1.34	1.58	2.79	2.40	1.65	2.13	4.76	3.49	0.00	0.00
14	40	40	230	6	110	10	41.58	145.33	1.49	0.98	2.91	1.33	1.90	1.34	2.73	1.69	0.00	0.00
15	40	40	230	16	109	14	41.62	144.65	0.89	0.45	0.23	0.38	0.96	0.47	0.19	0.41	—	—
16	40	40	230	16	109	14	41.38	144.28	0.02	0.14	0.00	0.19	0.00	0.13	0.00	0.23	—	—
17	40	40	230	6	109	10	41.35	144.97	0.00	0.29	0.90	0.70	0.06	0.36	0.16	0.63	—	—
18	40	40	230	6	109	10	41.12	144.60	0.00	0.10	0.11	0.28	0.00	0.10	0.00	0.26	—	—

*After Tanioka *et al.* (2004a).

amplitudes are smaller at Hachinohe, Tsukihama and Onagawa. In order to seek for a better agreement at these stations, we make another case in which we use only 4 stations (the above three plus Kushiro). For Tsukihama and Onagawa, we only use the first half cycle of the waveform. The computed waveforms from this case reproduce the observed ones (Fig. 7). The slip distribution estimated from these 4 stations is slightly different from the above estimates, but all the slips on subfaults F through J off Akkeshi are more than 4 m (Table 1). This indicates that a solution that can reproduce the amplitudes at Hachinohe, Tsukihama and Onagawa, where the inversion using 12 stations cannot reproduce the first amplitudes, still requires large slip off Akkeshi. In the following, we only consider the solution from 12 stations.

The 10 block and 18 block models have common features that they both have large slip in Tokachi-oki and the slip extend off Akkeshi, to the east of Kushiro submarine canyon. The details of the slip distribution are different, probably reflecting the spatial resolution of the subfaults. In any case, both the slip distribution and seafloor deformation are very different for the 1952 and 2003 Tokachi-oki earthquakes.

For the 18 block model, two uplift peaks exist off Akkeshi and Tokachi-oki. For the 2003 Tokachi-oki earthquake, the peak appears only in Tokachi-oki (Fig. 6). The waveforms computed from the 18 block model also reproduce the observed waveforms (Fig. 8). In order to examine the effects of slip distribution on the waveforms, we also compute tsunami waveforms from the model of the 2003 Tokachi-oki earthquake (Tanioka *et al.*, 2004a). The com-

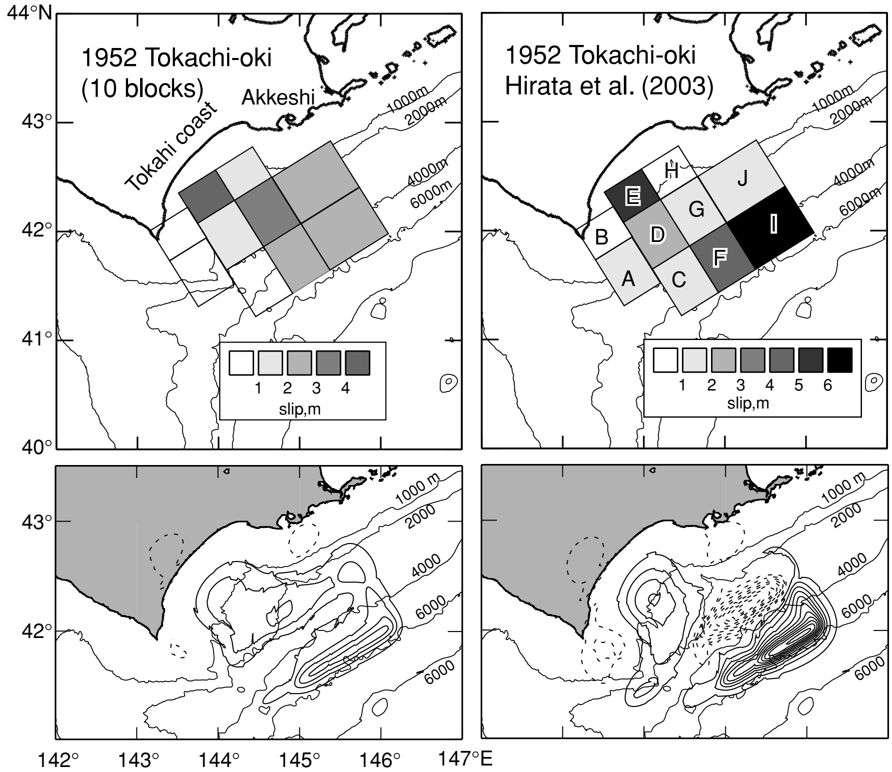

Fig. 5. Slip distribution on 10 blocks (upper panels) and computed seafloor displacement (lower panels) for the 1952 Tokachi-oki earthquake. Right panels are those by Hirata *et al*. (2003) and left panels are reanalyzed in this study. The contour interval for seafloor displacement is 0.2 m for uplift (solid curves) and 0.1 m for subsidence (dashed curves).

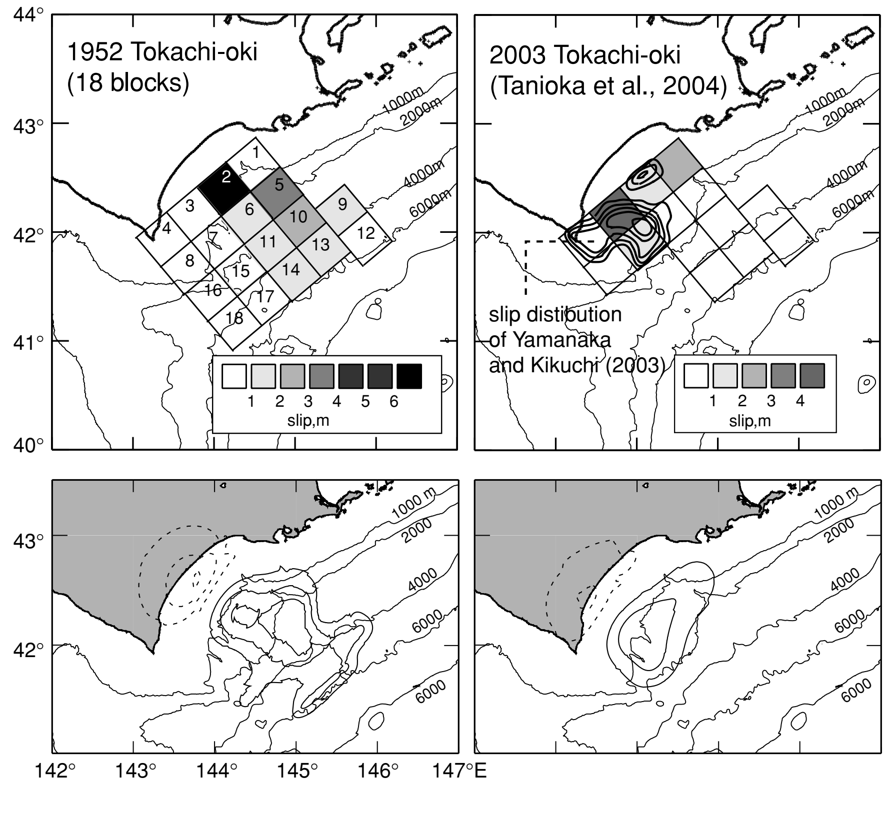

Fig. 6. Slip distribution on 18 blocks (upper panels) and computed seafloor displacement (lower panels) for the 1952 Tokachi-oki earthquake (left) and the 2003 Tokachi-oki earthquake (right: Tanioka *et al*., 2004a). The contour interval for seafloor displacement is 0.2 m for uplift (solid curves) and 0.1 m for subsidence (dashed curves). In the upper-right figure, slip distribution estimated from seismic waves (Yamanaka and Kikuchi, 2003) are also shown (contour interval: 1 m).

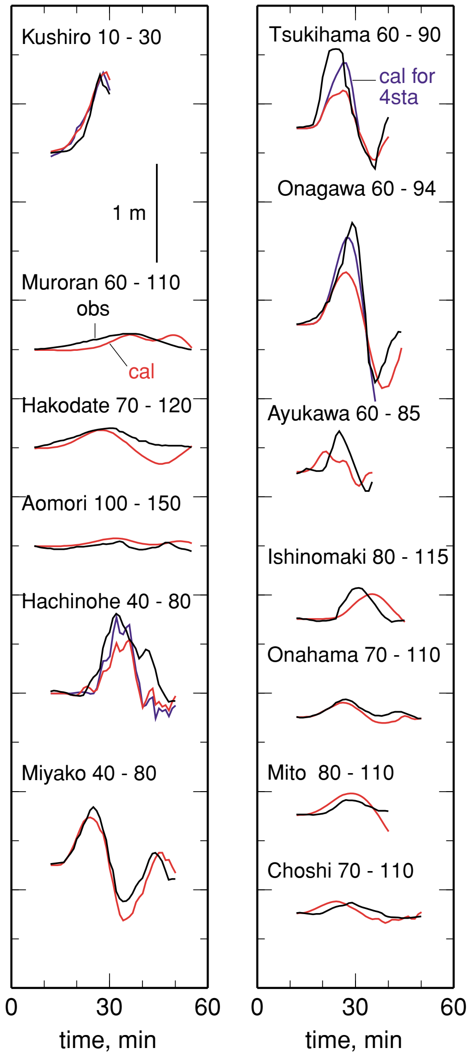

Fig. 7. Comparison of observed (black curve) and computed (red curves) waveforms for the 10 block model of the 1952 Tokachi-oki earthquake. The blue curves for Kushiro, Hachinohe, Tsukihama and Onagawa are the computed waveforms from the slip distribution estimated from these four stations only (4 sta in Table 1). The numbers next to the station names indicate the time window (in minutes from the earthquake origin time).

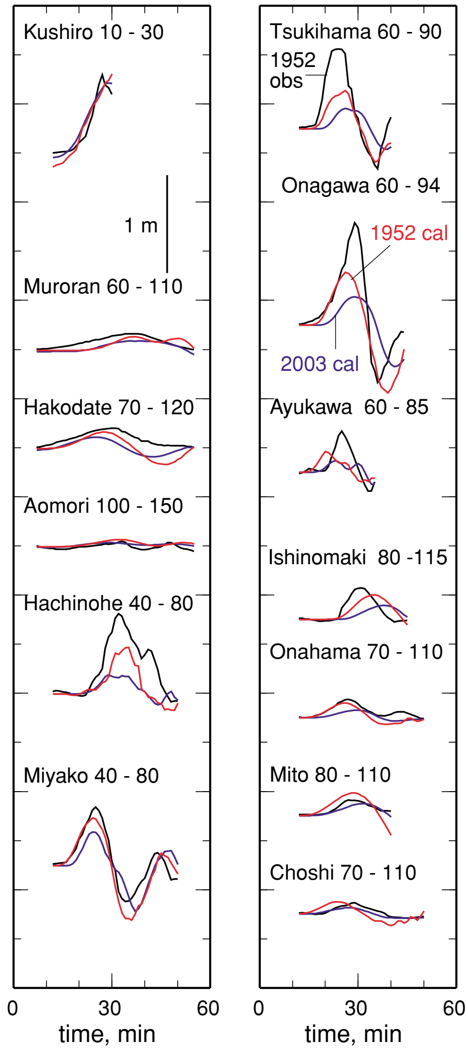

Fig. 8. Comparison of observed (black curve) and computed (red curves) waveforms for the 18 block model of the 1952 Tokachi-oki earthquake. The blue curves are the computed waveforms from the slip distribution for the 2003 Tokachi-oki earthquake (Tanioka *et al.*, 2004a). The numbers next to the station names indicate the time window (in minutes from the earthquake origin time).

puted amplitudes from the 2003 source are smaller than the 1952 tsunami, both observed and computed, particularly at Hachinohe, Tsukihama and Onagawa.

The seismic moment of the 1952 earthquake can be computed as 1.7×10^{21} Nm (corresponding to Mw 8.1) for the 10 block model, while 1.1×10^{21} Nm (Mw 8.0) for the 18 block model, assuming that the rigidity near the fault is 3×10^{21} N/m^2. These amounts are slightly smaller than the estimate (1.87×10^{21} Nm) by Hirata *et al.* (2003). Tanioka *et al.* (2004a) estimated the total seismic moment of the 2003 earthquake as 1.0×10^{21} Nm, by assuming a larger rigidity (6.5×10^{21} N/m^2). If such a large rigidity is assumed, the seismic moment of the 1952 earthquake becomes larger (2–4×10^{21} Nm or Mw 8.2–8.3).

5. Comparison with Coastal Heights

In addition to the tsunami waveforms recorded on tide gauges, coastal tsunami heights were measured for both the 1952 and 2003 earthquakes (Central Meteorological Agency, 1953; Kusunoki and Asada, 1954; Tanioka *et al.*, 2004b). On the Tokachi coast, the tsunami heights were 2–4 m and almost uniform for the both events. To the east of Kushiro, they are very different. The 2003 heights were less than 2 m except for one locality (Mabiro), while the 1952 heights were 2–7 m and varied from place to place. The largest tsunami height in 1952 was measured at Senpoushi, around the Akkeshi Bay. The 1952 tsunami caused significant damage in Akkeshi and Kiritappu, partly because offshore floating ice was carried ashore during tsunami inundation.

We compute coastal tsunami heights from the 1952 and 2003 source models estimated from the tsunami waveform inversions and compare them with the measured heights. For this computation, we use the nonlinear shallow-water (long-wave) equations with the finest grid size of 225 m along the coast. Runup on land or moving boundary is not included.

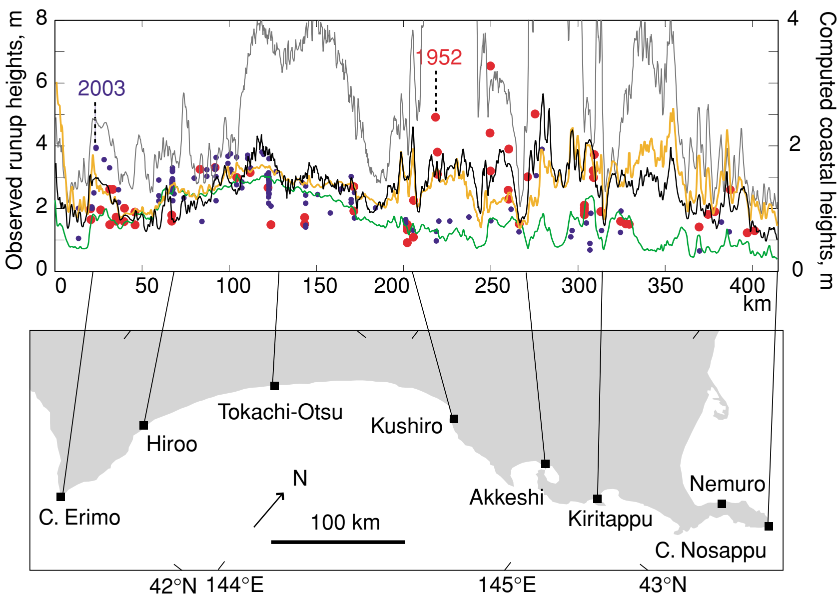

Fig. 9. The tsunami heights along the Pacific coast of Hokkaido. Red and blue dots are the measured heights for the 1952 and 2003 Tokachi-oki earthquakes (Tanioka *et al.*, 2004b; Central Meteorological Agency, 1953; Kusunoki and Asada, 1954). Green curve is computed height for the 2003 Tokachi-oki earthquake from the slip distribution of Tanioka *et al.* (2004a). Black and orange curves are computed for 10 block and 18 block models, respectively, of the 1952 earthquake. The gray curve is computed for the slip distribution of Hirata *et al.* (2003). Note that the measured height (left axis) and computed heights (right axis) are in different scale.

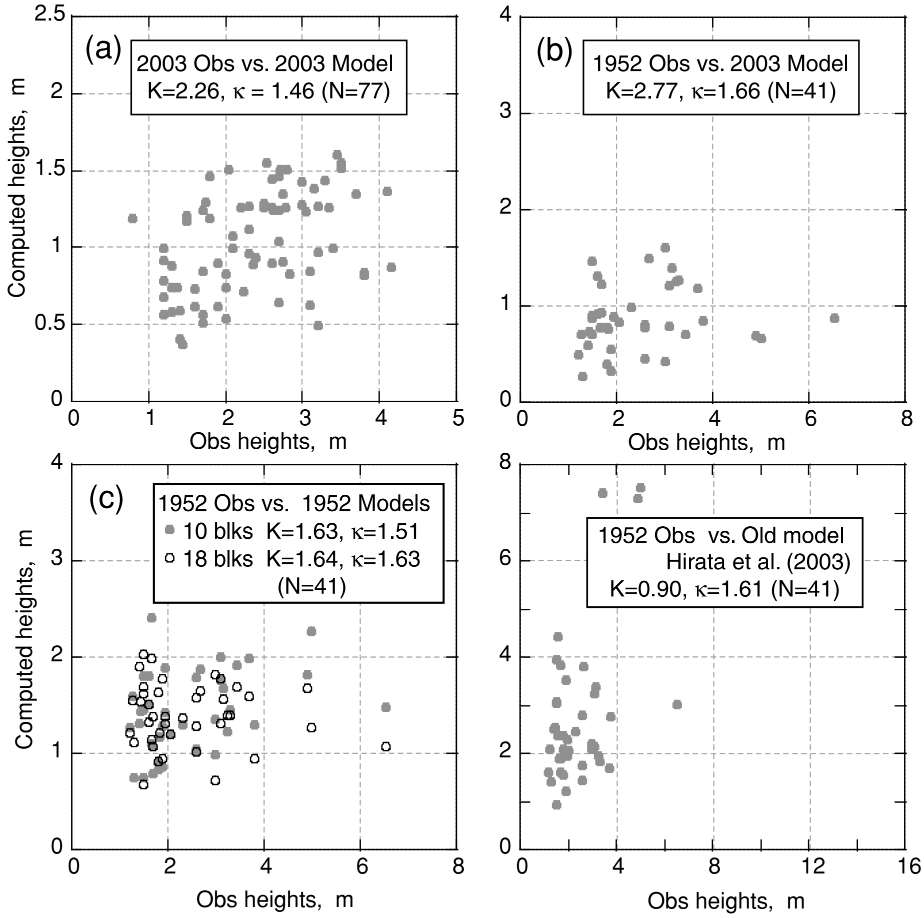

Fig. 10. Comparisons of the observed and computed coastal heights. (a) The 2003 Tokachi-oki earthquake. Measured heights are from Tanioka *et al.* (2004b) and computed heights are from slip distribution of Tanioka *et al.* (2004a). (b) The 1952 measured heights (Central Meteorological Agency, 1953; Kusunoki and Asada, 1954) and computed from the 2003 model. (c) The 1952 measured heights and computed heights. (d) The 1952 measured heights and computed heights from slip distribution of Hirata *et al.* (2003). Geometric average K, geometric standard deviation κ, and sample number N are also shown.

The coastal tsunami heights computed from the 2003 Tokachi-oki source model (Tanioka *et al.*, 2004a) reproduce the general pattern that tsunami heights are larger to the west of Kushiro compared to the east (Fig. 9). However, the amplitudes are smaller than the measured heights. Comparison of the computed and measured heights (Fig. 10) indicates that the computed heights are on the average about a half of the measured heights. For the comparison of observed and computed tsunami heights, geometric average K and geometric standard deviation κ, which can be considered as error factor, are often used (Aida, 1978). For 77 measurements made for the 2003 tsunami, $K = 2.26$ and $\kappa = 1.46$, indicating that measured heights are on the average more than twice larger than the computed.

There are several possible reasons for this discrepancy between the measured and computed tsunami heights. Our computation does not include tsunami runup to land, while some of the measurements were made on land. The grid size of our coastal computation (225 m) may not be small enough to reproduce the local variation of tsunami heights; Satake and Tanioka (1995) showed that the amplification factor is up to 2 for $6''$ grid (140 m by 190 m) and up to 3 for $20''$ (450 m by 620 m) grid. In addition to these computational aspects, the tsunami source estimated from the waveform inversion might not be able to reproduce the maximum tsunami heights. The measured coastal heights are the maximum heights while the tsunami inversion fits the waveforms for the first cycle or two. The maximum tsunami heights are often due to edge waves, later phase propagating on shallow shelf, whose characteristics depend on the source heterogeneity. Unknown tide gauge response might have affected short period components of the tsunami waveforms. We therefore employ different axes for the measured and computed heights in Fig. 9.

Computed coastal heights for the two models, 10 and 18 block models, of the 1952 earthquake are very similar (Fig. 9). They reproduce the general pattern that tsunamis heights were relatively uniform west of Kushiro but variable to the east. The amplitudes are again much smaller than the measured. The 10 block model yields $K = 1.63$ and $\kappa = 1.51$ while the 18 block model yields $K = 1.64$ and $\kappa = 1.63$ (for 41 points), indicating that the measured heights are on the average 1.6 times of the computed. The κ value, error factor, is slightly smaller for the 10 block model, indicating that the 10 block model is better to fit the coastal measurements. The computed heights from Hirata *et al.* (2003) model is similar to the measured heights, but the above comparison of the 2003 heights indicates that the computed heights may be overestimated. If we compare the computed heights from the 2003 Tokachi-oki earthquake model with the 1952 measured heights, the error factor κ becomes the largest (1.66). This indicates that the 2003 source model, which has slips located only to the west of Kushiro submarine canyon, cannot reproduce the measured tsunami heights in 1952. The 1952 tsunami heights can be better reproduced by a source model with slips extending to the east of Kushiro submarine canyon.

6. Conclusion

We reanalyzed the tsunami waveforms from the 1952 Tokachi-oki earthquake. From the comparison and alignment of the 1952 and 2003 waveforms, we estimated the clock errors of the 1952 tide gauges and applied the corrections. We adopted high-resolution tsunami simulation, similar to that used by Tanioaka *et al.* (2004a) for the 2003 tsunami. The results indicated that for both 10 and 18 block models, the slip extended to the east of Kushiro submarine canyon. Comparison of the coastal tsunami heights and computed coastal heights also supports this slip off Akkeshi.

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