ANNALS OF GEOPHYSICS, VOL. 47, N. 2/3, April/June 2004

Detection of Kuril subduction-zone earthquakes from remote historic records in Honshu, Japan, between 1656 and 1867

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Abstract
Earthquakes before A.D. 1800 along the Southern Kuril trench, although before the start of written history on nearby islands, probably account for some of the earthquakes noted by local records in Honshu, hundreds of kilometers to the southwest. Earthquake historians have identified about 4800 felt earthquakes in Edo (present Tokyo) and about 3000 felt reports in selected local government records in Tohoku, northern Honshu, for the years A.D. 1656-1867. On the average, 19 earthquakes per year were felt in Edo. Of the Tohoku records, 361 (an average nearly 2 per year) were felt at multiple Tohoku locations; 95 of these (0.4 per year) were also felt in Edo. Since 1926, Tokyo has had a yearly average of 15 felt earthquakes with seismic intensity 2 or more on the Japan Meteorological Agency scale (corresponding to III or more on Modified Mercalli scale). For Tohoku the average annual frequency is about 4. Among them, an average of 0.6 events per year also reached intensity 2 in Tokyo. About one quarter of these events occurred in the southern Kuril trench. If the seismicity is temporally constant, about 80 of the earthquakes recorded in 1656-1867 probably had a Kuril origin.

Key words *historical earthquakes – seismic intensity – seismicity – Kuril subduction zone*

1. Introduction

Japan is one of the most seismically-active regions in the world, surrounded by four tectonic plates: the Pacific, Philippine Sea, Eurasia and North America plates (fig. 1). The last two, on which most Japanese islands are situated, are also known as the Amurian and Okhotsk plates, respectively (Seno *et al.*, 1996; Heki *et al.*, 1999). Most of great (M~8) earthquakes around Japan occur in subduction zones, including the Kuril trench where the Pacific plate subducts beneath Hokkaido, and the Nankai trough where the Philippine Sea plate subducts beneath southwest Japan.

Japanese historical records document earthquakes as far back as the 7th century (Usami, 2002). Until around A.D. 1600, most historical records were kept in western Japan, particularly around Kyoto where the emperor's capital was located between the 8th and 19th centuries. Hence many earthquakes were reported in Kyoto and its vicinity. On the basis of such historical documents, recurrence of great earthquakes along the Nankai trough with approximately 100 year intervals has been inferred from historical documents (Imamura, 1928; Ando, 1975). In A.D. 1603, the Shugun established a centralized government in Edo (present Tokyo; fig. 1), and each local government started keeping official records. Both the quantity and quality of his-

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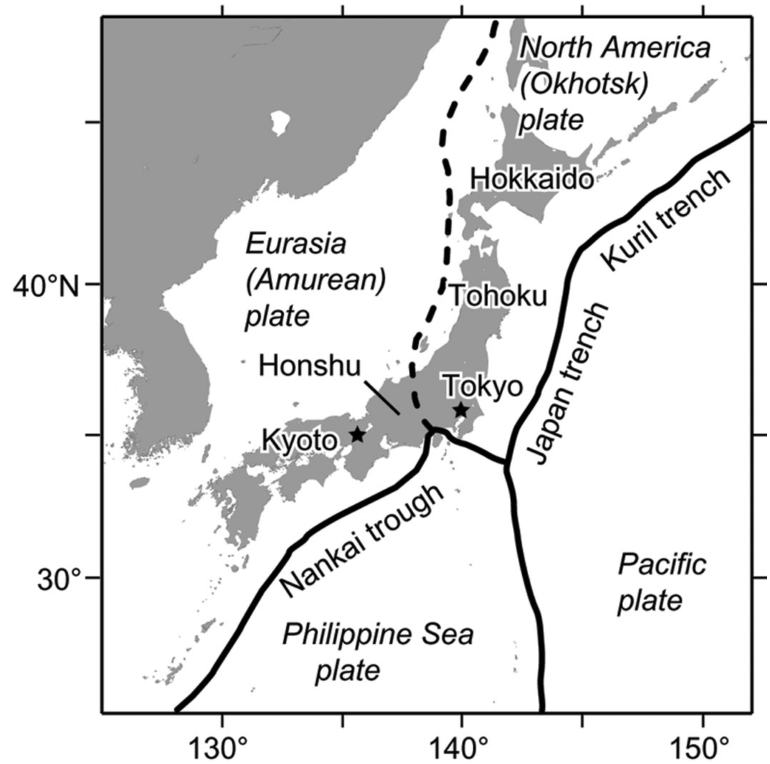

Fig. 1. Plate tectonic configuration around the Japanese Islands. The Pacific plate subducts beneath northern Honshu, the largest island, and Hokkaido, the northernmost island, at the Japan and Kuril trenches, respectively. The Philippine Sea plate subducts beneath southwestern Japan at the Nankai trough.

torical records dramatically increased in the Edo period (A.D. 1603-1867), and earthquakes were documented throughout Japan except for Hokkaido (fig. 2).

The oldest documented earthquakes along the Southern Kuril trench occurred in the 19th century. Great earthquakes along the southern Kuril trench cause damage from ground shaking and tsunamis on nearby Hokkaido. Most of Hokkaido had long been occupied by native people (Ainu) and very few written records existed until the 19th century. The oldest record in the Eastern Hokkaido is «Nikkan-ki», the official record of a temple in Akkeshi. It started in A.D. 1804, and reports about 70 earthquakes between 1816 and 1861. The earthquake record, however, is not uniform: 32 events were recorded between 1816 and 1821, followed by ten years with no reported earthquakes.

In this paper I attempt to detect the Kuril earthquakes from remote historical data. Because of the short written history of Hokkaido, it seems difficult to infer the pre-19th century seismicity along the Kuril trench. However, great earthquakes along the southern Kuril trench are felt in Tohoku (northern Honshu) and Tokyo, and relatively uniform historical records exist in these regions. The seismic intensity distribution is examined from the Edo-period and modern data. Then an attempt is made to detect the Kuril earthquakes hidden in the historical earthquake records in Tohoku and Edo.

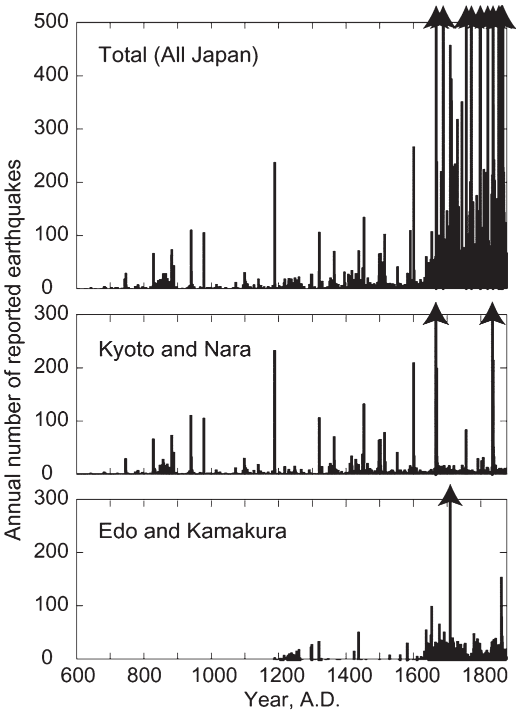

Fig. 2. Yearly number of earthquake reports since the 7th century. The top figure shows total records for all Japan, the center figure is for Kyoto (including Nara), and the bottom figure is for Tokyo (including Kamakura). Historical earthquake data exists since around 7th century in the southwestern Japan, mostly around ancient capital of Kyoto. Since A.D. 1603 (in Edo period), historical data are available throughout Japan with exception for Hokkaido. Historical records exist only after A.D. 1800 in Hokkaido. Data are from Ueda and Usami (1990).

2. Earthquakes along Kuril subduction zone

Along the Kuril trench, where the Pacific plate subducts at a rate of about 8 cm/yr beneath Hokkaido (Seno *et al*., 1996), great ($M \sim 8$) earthquakes repeatedly occurred in the 19th and 20th centuries (Kanamori, 1977; Fukao and Furumoro, 1979) (fig. 3). In the 20th century, five great interplate earthquakes occurred between 1952 and 1973. It should be noted that great earthquakes also occur within the subducted slab (*e.g.*, in 1993 and 1994) and cause ground shaking and tsunami similar to those from interplate earthquakes (Satake and Tanioka, 1999). Great earthquakes also occurred in the 19th century (fig. 3), but their exact location, size and mechanisms are not well known.

The Kuril earthquakes are associated with unusual intensity distributions. The isoseismals are not concentric around the epicentre, but are elongated along the Japanese arc because of the lower attenuation of seismic waves in the subducting Pacific plate (Utsu, 1971).

Figure 4 shows an example for the 1952 Tokachi-oki earthquake (M_w 8.1). Seismic intensity 5 (on the Japan Meteorological Agency scale; see fig. 4 for conversion to the Modified Mercalli scale) was recorded on the Pacific coast of Hokkaido near the source, and regions of intensity 4 and 3 extend along the western Hokkaido and northern Honshu. This earthquake was felt as far as at Tokyo, where intensity 2 on the JMA scale was registered.

Large Kuril earthquakes also cause tsunami damage on the Pacific coasts of Hokkaido and northern Honshu. The tsunami heights from the 1952 earthquake were mostly 2-4 m on the Hokkaido coast and 1-2 m on the northern Honshu coast (Watanabe, 1998). The tsunami caused extensive damage on Hokkaido's Pacific coast and lesser yet noticeable damage on Tohoku's Sanriku coast.

3. Historical records

Japanese historical documents describing earthquake damage have been systematically collected and published in three different phases: in 1899-1904 by Tayama, in 1941-1951 by Musha, and in 1980-1994 by Usami and his colleagues (Usami, 2002). The latest compilation, led by Usami, «Collection of Materials for the History of Japanese Earthquakes» (21 volumes) was published from Earthquake Research Institute, University of Tokyo. The number of earthquakes (damage or felt reports) has dramatically increased in these three stages: approximately 1900, 8400 and 45 000. On the basis of these documents, seismic intensity at each location is estimated from descriptions of ground shaking and damage. The size and epicentre of earth-

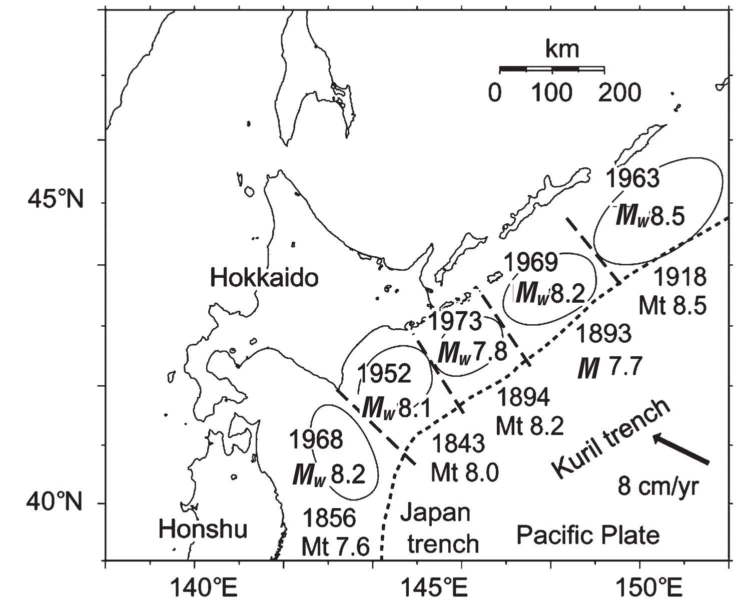

Fig. 3. Source regions of great interplate earthquakes along the southern Kuril trench. The 1968 and 1856 earthquakes occurred around the corner of Kuril and Japan trenches. Magnitudes are M_w (moment magnitude) for the 20th century events and Mt (tsunami magnitude; Abe, 1999) for the 18-19th century events except for the 1893 event for which *M* was estimated by Utsu (1999).

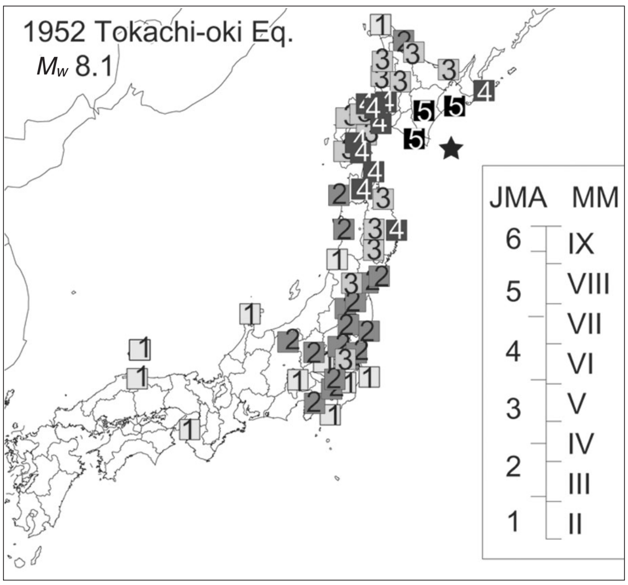

Fig. 4. Seismic intensity distribution (on the Japan Meteorological Agency scale) of the 1952 Tokachi-oki earthquake. Conversion table for the JMA and Modified Mercalli scales is also shown.

quakes are further estimated from the seismic intensity distribution, by comparing modern earthquake data and using empirical relations. As a result, several tables of damaging earthquakes in Japan have been published (Usami, 2002).

The seismic intensity distribution of some historical earthquakes in Tohoku is similar to that of modern Kuril earthquakes (fig. 5). An earthquake on 15 April 1674 caused slight damage to the castle at Hachinohe, corresponding to seismic intensity 5 on JMA scale. The earthquake was strongly felt (intensity 3-4) in Tohoku and slightly felt (intensity 2) in Edo. On the basis of the intensity distribution, Usami (2002) estimated the epicentre off Hachinohe with $M \sim 6$. Another earthquake on 10 November 1692 was also felt strongly in Hachinohe without causing any damage (intensity 4); it was slightly felt (intensity 2) in Edo. Without any documented damage, this earthquake has not been included in the tables of damaging earthquakes, and neither the epicentre nor magnitude has been estimated. Although the spatial extent is limited, the intensity distributions suggest a possibility of Kuril origin of both of these earthquakes.

I examined selected historical documents that continuously recorded earthquakes in the Edo period. At Hirosaki, the official record of local government, «Tsugaru-han On'nikki» (about 3300 volumes) is a daily record of various events for 204 years (A.D. 1661-1864). Earthquake and tsunami damage in the territory was described in detail in this record. Even if no damage was caused, earthquakes were noted in daily records along with weather of the day. Such earthquake reports are found in about 1300 days during the 204 years, an average of 6.4 days per year (fig. 6). The daily records sometimes describe multiple earthquakes without specifying the exact number (*e.g.*, «a few» or «several»), hence I decided to count the number of days («earthquake days») rather than number of earthquakes. Similar documents report earthquakes on 730 days, or average of 3.6 days per year, at Hachinohe, and 950 days in total or average of 6.2 days per year at Morioka. In Edo, various records report about 4800 earthquakes in the Edo period, an average of 19 events per year (Ueda and Usami, 1990; fig. 6). Continuous records were also kept at

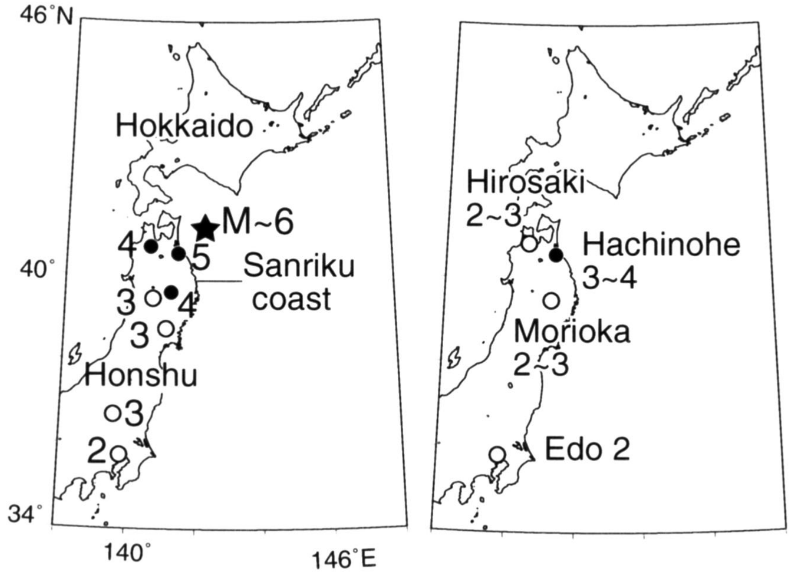

Fig. 5. Seismic intensities estimated from historical documents for an earthquake on 15 April 1674 (left) and 10 November 1692 (right). For the 1674 event, epicentre (star) and M estimated by Usami (2002) are also shown.

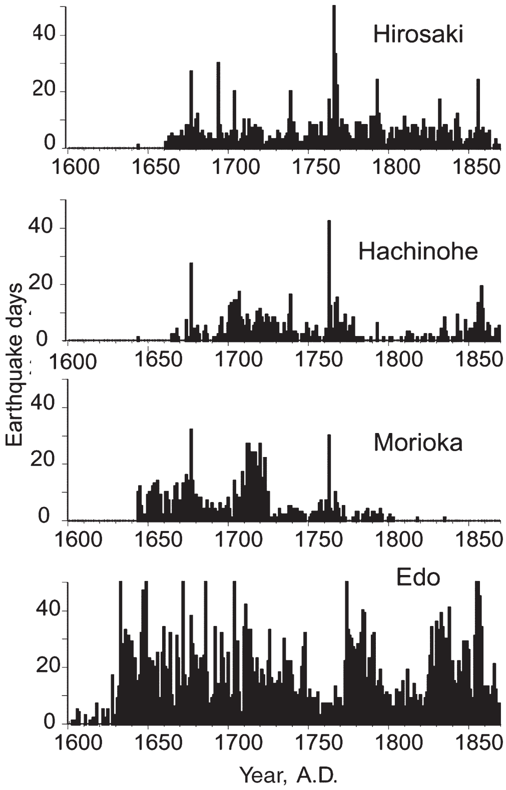

Fig. 6. Annual frequency of days in which earthquakes were recorded in historical documents in three Tohoku locations (Hirosaki, Hachinohe, and Morioka) and Edo (Tokyo). See fig. 5 for the locations.

Nikko, where guards of the first Shogun's graveyard kept daily records.

From the list of earthquakes individually recorded in Tohoku and Edo, I selected those reported at multiple locations. If earthquake descriptions from different locations or documents differ by up to one unit of time, a «Koku», or about two hours, I assume that they represent the same earthquake. Of the about 3000 descriptions from three localities in Tohoku, more than 2000 were reported at only one location and seem to be of local origin. During the 212 years between 1656 and 1867, there are 361 events recorded at multiple locations in Tohoku region (fig. 7). Of these, 95 events were also recorded in Edo or Nikko.

Among the 361 events recorded at multiple locations, epicentres for 52 events have been previously estimated on the basis of damage and intensity distributions (Usami, 2002). Additionally, about 20 events have been located off Hachinohe (fig. 5), but these could be of Kuril origin, as discussed earlier. The earthquakes with known epicentres include great ($M \sim 8$) earthquakes along the Japan trench. Along the northern Japan

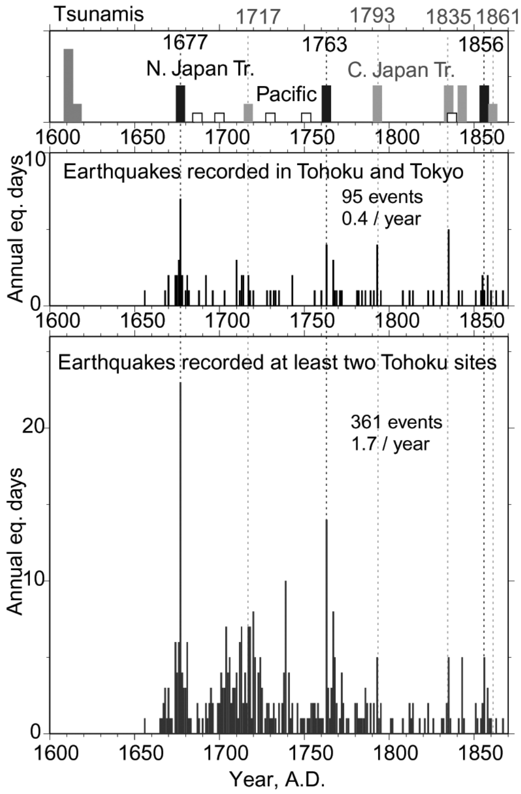

Fig. 7. Annual frequency of earthquakes recorded at multiple locations. The bottom panel shows those recorded at least two locations in Tohoku. The central panel is for those recorded at multiple locations in Tohoku and Edo (Tokyo). The top panel indicates tsunami damage on the Sanriku coast. The white bars are trans-Pacific tsunamis, black bars are those from northern Japan trench and gray bars are from central Japan trench.

trench, at the source area of the 1968 event (fig. 3), great ($M \sim 8$) earthquakes and their aftershocks occurred in 1677, 1763, and 1856. To the south along the central Japan trench, the Miyagi-oki earthquakes occurred in 1717, 1793, 1835 and 1861 in the Edo period, followed by 1897, 1936 and 1978 events (Utsu, 1999).

During the Edo period 16 tsunamis were recorded on Sanriku, the Pacific coast of northern Honshu, but the origin of these tsunami are all known (Watanabe, 1998). Among these, five tsunamis (1687, 1700, 1730, 1751 and 1837) were trans-Pacific tsunamis from North or South America, supported by historical or paleoseismological evidence. Four were from great earthquakes in the northern Japan trench (including one from the 1763 aftershock) and other four were from the central Japan trench. The 1611 tsunami has been considered to be from a tsunami earthquake (Watanabe, 1998). A tsunami in 1616, though included in Watanabe (1998), has been questioned of its existence (Yoshinobu Tsuji, manuscript in revision). The last one, in 1843, is considered to be from the penultimate event of the 1952 Tokachi-oki earthquake along the southern Kuril trench (fig. 2). Unknown Kuril earthquakes in the Edo period, if any, apparently did not generate damaging tsunamis along the Sanriku coast, because such tsunami damage would have been documented.

4. Modern seismic intensity observations

The Japan Meteorological Agency started systematic seismic intensity observations in 1926 at weather stations distributed throughout Japan. I used the JMA seismic intensity database (Ishigaki and Takagi, 2000) for the 76 years 1926-2001, and compared the modern and historical felt reports. Because there was no weather station in Hirosaki, I used nearby Aomori data. At Aomori, Morioka and Tokyo, the seismic intensity data have been available since 1926, but the Hachinohe data have been available only since 1936.

The JMA seismic intensity observations detect more earthquakes than the historical reports. The average annual frequency of earthquakes with intensity 1 or more on JMA scale is 18 at Aomori, 48 at Hachinohe, 37 at Morioka, and 40 at Tokyo (table I; fig. 8). If the threshold is raised to seismic intensity 2 (corresponding to III on Modified Mercalli scale), then the average annual frequency becomes 7 at Aomori, 18 at Hachinohe, 13 at Morioka, and 15 at Tokyo. These numbers are comparable to annual earthquake days in the historical documents: 6.4, 3.6, 6.2 and 19, respectively, at these locations. It indicates that historical data are complete for modern seismic intensity 2 or higher, if the seismicity is assumed to be temporally constant. At Hachinohe and Morioka, the modern records show high-

Table I. Felt earthquakes of historical and modern JMA data.

	Historical data		JMA seismic intensity observation			
	Annual frequency	Period	1 or higher	2 or higher	3 or higher	Period
Hirosaki	6.4	1661-1864	17.5	7.2	1.9	Aomori: 1926-2001
Hachinohe	3.6	1665-1869	48.2	17.6	4.1	1936-2001
Morioka	6.2	1664-1796	37	13.1	3.4	1926-2001
Tokyo (Edo)	19	1601-1872	39.9	14.9	4.1	1926-2002
Tohoku	1.7	Two or more	9.8	3.6	0.9	Aomori, Hachinohe, Morioka
Tohoku and Tokyo	0.4		1.4	0.6	0.1	Above three and Tokyo

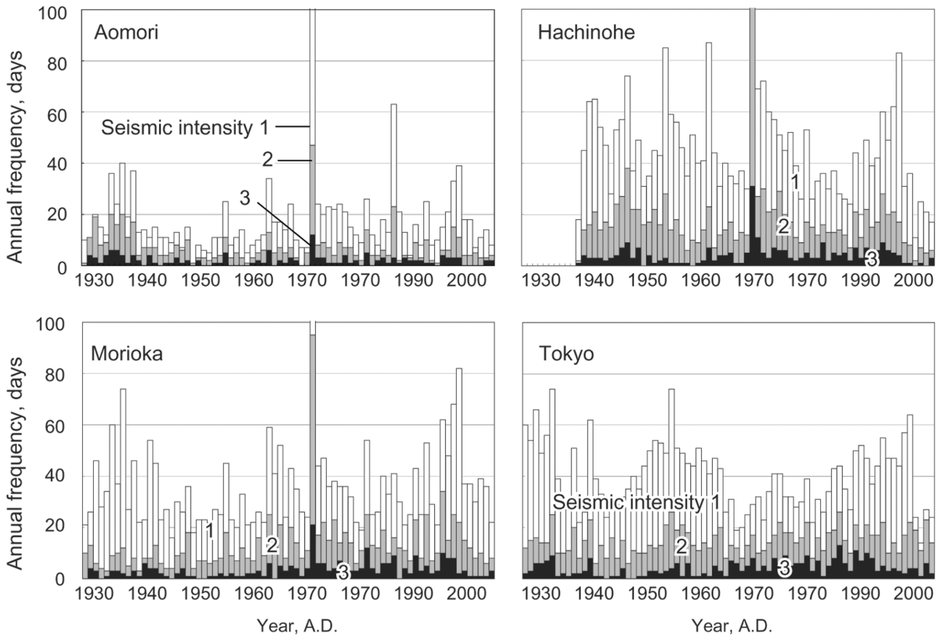

Fig. 8. Annual frequency of felt earthquakes reported by Japan Meteorological Agency (1926-2001). Shading indicates different intensity values on the JMA seismic intensity scale.

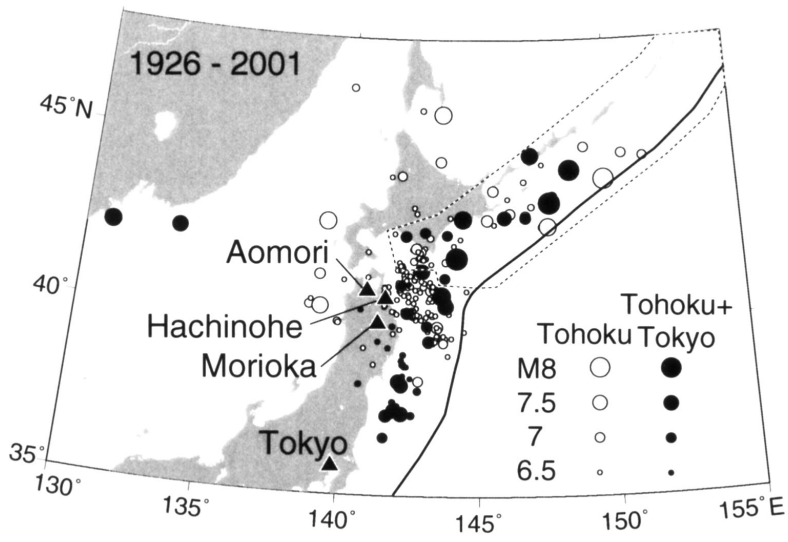

Fig. 9. Epicentre distribution of earthquakes reported at three stations in Tohoku (open circles) and those reported at Tohoku and Tokyo stations (solid circles). The symbol size is proportional to earthquake magnitude. Triangles indicate the station locations. Nearly a quarter of these events occurred along the Kuril trench, in the region surround by dashed lines.

er numbers; hence the historical data may be complete for intensity 3 or higher, for which the average annual frequency is 4 at both locations. However, considering the slight difference in counting methods (events in modern data whereas earthquake days that possibly contain multiple events in historical data) and the incompleteness of historical data, I conclude that historical data detect earthquakes with seismic intensity of 2 or higher on the JMA scale.

Earthquakes recorded at multiple JMA stations yield similar conclusions. During the 66 years between 1936 and 2001, the number of felt earthquakes at the three Tohoku stations (Aomori, Hachinohe and Morioka) is 276 if the threshold is intensity 2, and 68 for the threshold intensity of 3. The average annual frequencies are 4 and 1, respectively, comparable to that from historical data: 1.7. The number of events recorded at Tohoku stations and Tokyo is 46 and 11 for intensity thresholds of 2 and 3, respectively. The annual frequencies are 0.6 and 0.1 events, again comparable to that of historical data, 0.4.

Epicentres of earthquakes felt in Tohoku and Tokyo are distributed around northeast Japan (fig. 9). Many earthquakes are located on the Pacific coast of Hokkaido and Honshu, but inland earthquakes, earthquakes along the eastern margin of Japan Sea, and deep events beneath the Russian coast are also included. Among them, 59 events (21%) of those felt (with intensity scale 2 or larger) only in Tohoku, and 11 events (24%) of those felt in both Tohoku and Tokyo occurred along the southern Kuril trench.

5. Edo-period Kuril seismicity

A comparison of historical and modern earthquakes suggests historical data detect earthquakes with seismic intensity of 2 or more on the JMA scale. Under an assumption that the historical data are complete for this threshold, and further that the seismicity rate has not changed since the 17th century, the number of Kuril earthquakes can be estimated for historical data set. Of the 361 earthquakes recorded at multiple Tohoku locations between A.D. 1656 and 1867, about 76 events (21%) are estimated to be of Kuril origin. Of the 95 events recorded at multiple Tohoku locations and Edo, about 23 events (24%) are also estimated to be of Kuril origin.

Are the above assumptions, data completeness and temporally constant seismicity, valid? Regarding the second assumption, earthquakes often occur as clusters and the seismicity rate may change with time. In this study no declustering, including aftershocks, was made for either historical on modern records. Intraplate seismicity rate in Tohoku is reported to change with association of larger interplate earthquakes (Shimazaki, 1978). Because the time period is very long (> 200 years for the Edo records and 75 years for modern data), effects of clustering and temporal change may not be significant.

The present study cannot identify individual Kuril earthquakes, but the candidates are listed. Further investigation of historical documents could focus on these dates and might reveal more detailed information on individual earthquakes. Historical documents are still being found from local archives. While it is unlikely that continuous documents as used here are newly found, historical records for shorter period of time are likely to be found. The candidate tables will be therefore useful to examine such records.

Acknowledgements

The Japanese version of this paper with a table of the 361 events was published in Historical Earthquakes (*Rekishi Jishin*). The full text can be downloaded at http://staff.aist.go.jp/kenji.satake/Rekishijisin/05-Satake.pdf. Kazue Ueda provided me with her database for the index to the collections and a summary of felt earthquakes (fig. 2). Akimichi Takagi provided me with his software to analyze the JMA seismic intensity database. Yuichi Nishimura carefully reviewed the Japanese version of this paper. I thank two reviewers whose comments improved the presentations of the paper. I also thank Virginia García Acosta, Roger Musson, and Max Stucchi for their efforts to organize the workshop «Investigating the records of past earthquakes» and offering me an opportunity to participate.

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