HIGH-FREQUENCY HYDRO ACOUSTIC SIGNALS (40 – 110 HZ), PRECEDING EARTHQUAKES, ON THE PACIFIC SHELF OF THE KAMCHATKA PENINSULA*

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ABSTRACT

The local Kamchatka earthquake catalogue data and hydro-acoustic measurements obtained during the Acoustic Thermometry of Ocean Climate (ATOC) experiment were examined together. Time series of acoustic records made during or immediately before the earthquakes were analyzed. Two types of signals were obtained from the hydro-acoustic records: (1) micro-earthquakes (MEQ) whose focuses were located in the same area as the seismic focus of the main earthquake (EQ), and (2) seismic tremor, which starts before the main shock. The duration of MEQ was about 3-4 seconds. If the time interval between the hydro-acoustic records and the main earthquake shock was more than 4 hours, no MEQs were recorded.

OBSERVATIONAL DATA

To search the signals preceding large earthquakes, we used the data obtained from the Acoustic Thermometry of Ocean Climate (ATOC) experiment. The “Agam” hydrophone cluster developed by Morphyspribor was the main source of the experimental data. This cluster is situated on the Pacific shelf of the Kamchatka Peninsula [Demianovich, 1998; Karlik, 2002]. This 2-D cluster was submerged into the ocean and deployed a few meters from the bottom. The horizontal size of the cluster is 100 meters and vertical size is 17 meters. It was constructed to locate moving objects in the ocean. This cluster consists of more than 2000 hydrophones placed in a rectangular matrix. Hydrophones placed in one vertical line form a channel. To minimize the background noise, signals from one channel were summarized (see *Karlik* [2002] in the present volume for additional details). Channels were placed in a horizontal direction, so one can detect the azimuth of the signal recorded. Signal was recorded by all channels with a small lag. With this lag, the signals can easily be phased in the direction.

This cluster was in operation for a long time and recorded many signals associated with seismic events. However, until recently these signals have never been used to try to predict earthquakes and the respective data have never been analyzed to examine the situation before the earthquake (the data became unclassified only in 1998). The only way the hydrophone records were used for research purposes is analyzing T-phase of the tsunamigenic earthquakes.

In the present paper we use the data from the ATOC experiment for 1998-1999. In this experiment the propagation time from Hawaii to Kamchatka was examined and the signal/noise ratio was found to be quite small (less than 0.1), so the signal did not change the shape of the recorded noise [Virovlyansky *et al.*, 2000]. The sampling rate of the signal was 300 Hz, a bandpass filter from 50 to 100 Hz was applied to filter the data, 14 instrument channels were used.

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Altogether, 162 records were analyzed (all available data from the ATOC experiment). These data were recorded from July 12, 1998 to March 21, 1999. Each record contained 397,118 counts (about 1323.7 sec or a little more than 22 min). Data were recorded up to 6 times per day, namely at 2:54:20, 6:54:20, 10:54:20 GMT, etc. However, on some days there were no records and on some others there were only few. The records were from different seasons, daytime and weather conditions, so we could examine and exclude influence of external factors and detect seismic signals. Instead of using the common approach based on integration of short data segments, we preferred to store large amount of data and use spectral methods to select and analyze seismic signals.

COMBINED ANALYSIS OF KAMCHATKA EARTHQUAKES AND HYDRO-ACOUSTIC DATA

From the local Kamchatka earthquake catalogue we selected the part coinciding with the period of the ATOC experiment. The NEIC catalogue data were also used to locate major global earthquakes and to compare these events with hydro-acoustic data. The Kamchatka local catalogue contains events for the region (48° – 60° N 151° – 173° E) from class 4.7, however the reliable data are related only to the events of class 7.5 and higher. Magnitude of the earthquake may be expressed as Class = 4.6 + 1.5*M. From July12, 1998 to March 21 1999, there were 3058 events available. All these events were examined, 24% of all events were found to be less than 100 km from the antenna. Earthquakes are not a rare event in this region but most of the records are just oceanic noise.

The catalogue data from February 4 to 6, 1999, combined with a series of hydro-acoustic records are presented in Figure 1. Horizontal axis is the time in hours and vertical axis is the class of the earthquake. Vertical arrows show earthquake time, and six rectangles are the hydro-acoustic records. There were no earthquakes during these records but strong earthquakes occur just after five of six records.

Wavelet analysis was applied to all records to construct "spectrogram" and examine variations of spectra in time. All records were also listened to in a usual manner and all interesting events were selected and examined by amplitude using all channels simultaneously.

As the result of this analysis of all available data we detected one earthquake occurring specifically during the hydro-acoustic recording (October 20, 1998, 02:54:20) and several other records, which were followed by nearby earthquakes in less than 4 hours. For all these events we found that the sources of the hydro-acoustic signals were located near the earthquake epicenter zones.

HYDRO-ACOUSTIC SIGNALS CAUSED BY LOCAL EARTHQUAKES

Two types of hydro-acoustic signals preceding the main shock were detected: First type are micro earthquakes (MEQ) from the epicentral area with acoustic signals in the frequency range 40-75 Hz and duration of 3 to 4 sec. In the record of October 20, 1998, 02:54:20 GMT we found nine MEQs, which occurred before the main earthquake shock. The first MEQ occurred within 10 minutes before the earthquake and the last one within 38 sec before (Figure 2a). Micro earthquakes in hydro-acoustic records can be very easily detected due to their wide frequency range. An example of a micro earthquake is presented in Figure 2b. The second type is a tremor in the frequency range 30-40 Hz. This tremor begins within a few seconds before the main shock.

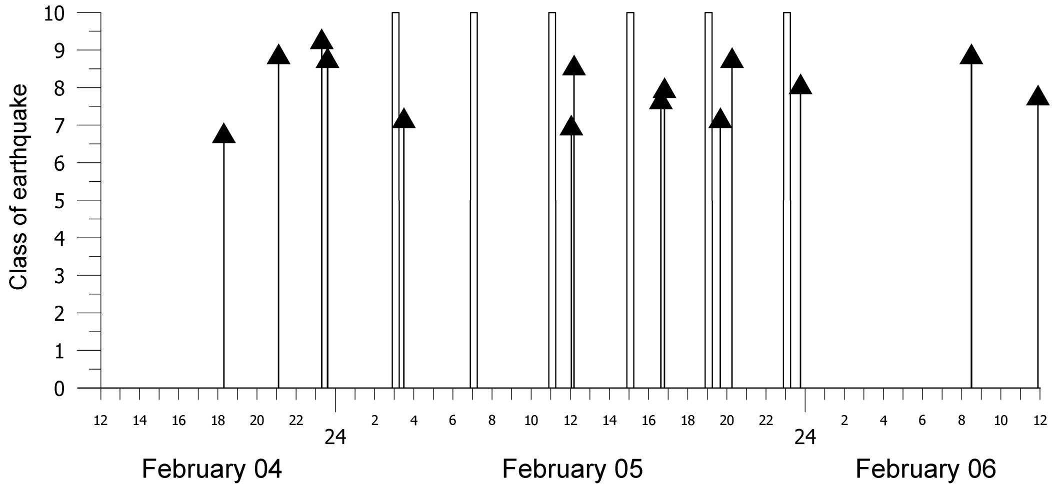

Figure 1. Earthquakes and times of the hydro-acoustic records from February 4, 1999 to February 6, 1999. Horizontal axis shows time in hours, and vertical axis presents class of the earthquake. Vertical arrows mark earthquakes from the local Kamchatka catalogue, rectangles are the times of the hydro-acoustic observations.

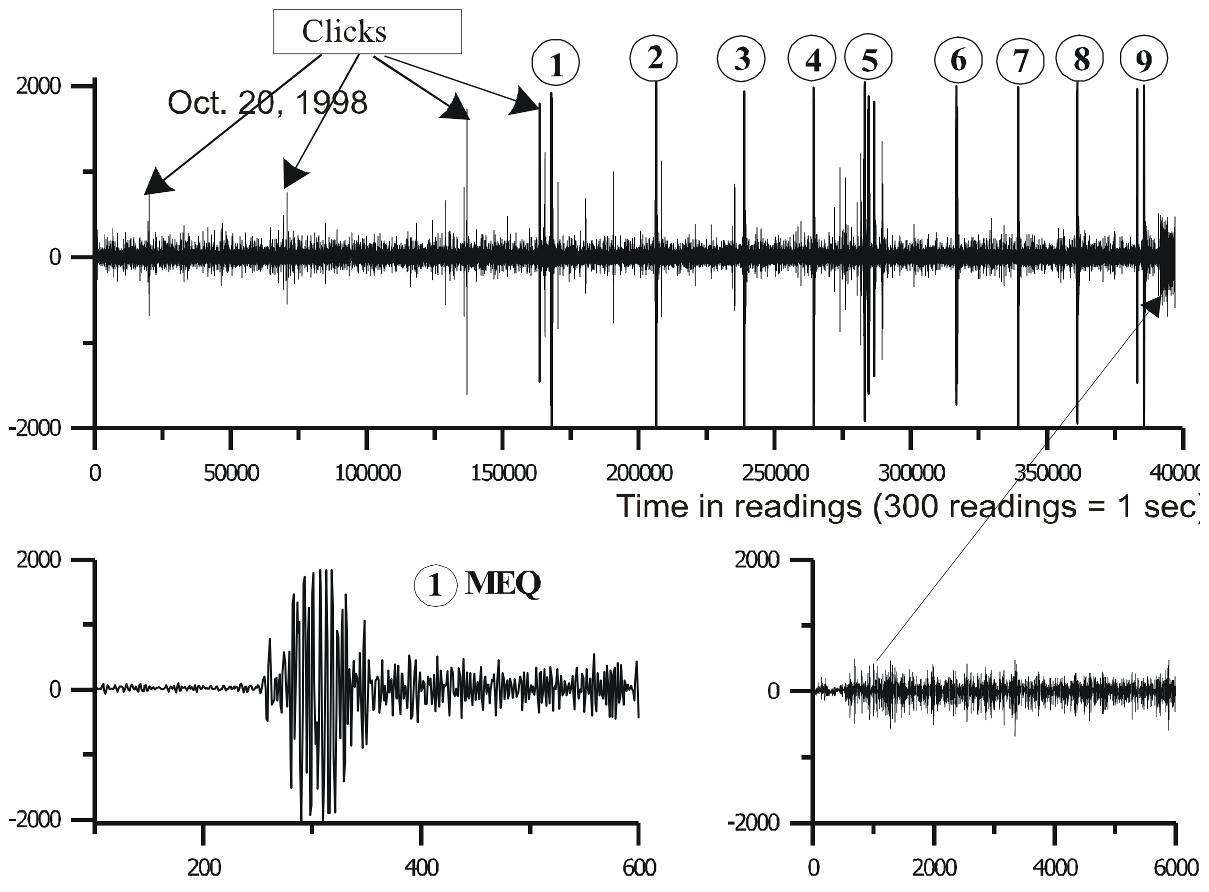

Figure 2. Hydroacoustic record of October 20, 1998, beginning time 02:54:20 GMT, Channel #14 (a) and two fragment of record: micro earthquake (b), and high frequency noise before the earthquake (c). Time in the horizontal axis is in samples (300 samples = 1 sec), vertical axis is the amplitude in mV.

The earthquake of October 20, 1998, 03:15:46 GMT occurred at the end of the hydro-acoustic record. The record ended at 03:16:24. According to the regional catalogue, this earthquake has class 10.3. The horizontal distance from the epicenter to antenna is 50.4 km, and from the hypocenter 129.23 km. The spectrogram of this record is shown in Figure 3a, and the record itself as the amplitude plot for the 14^{th} channel is shown in Figure 3d. The horizontal spectrogram axis has time in seconds, the vertical axis has frequency in Hz and the intensity of the black color shows the relative record energy. Nine intensive signals are shown by arrows in Figure 3a. High-frequency noise appears at the end of the record preceding the main earthquake shock.

The digital record of the first channel is presented in Figure 2a. This channel is much noisier than the 14th channel (Figure 3).

In Figure 2a one can see lots of clicks, i.e. parasite signals caused by the hardware. These "click" signals have similar amplitudes as micro earthquakes but are recorded only by one or a few nearby channels, in contrast to micro earthquakes, which are recorded simultaneously by all channels. Besides, all clicks are much shorter than the MEQ records. Encircled numbers in Figure 2a mark all micro earthquakes. The first micro earthquake is shown in Figure 2b but only partly (due to the record length). The end of the record in Figure 2a contains high-frequency noise, which is shown in detail in Figure 2c.

All nine earthquakes from our example (October 20, 1998) are recorded by all channels with approximately the same amplitude. This means that the size of the antenna is negligible in comparison with the distance to the source. The first six channel records of the first earthquake are shown in Figure 4. Vertical scale is the same for all channels and time is shown in samples (1/300 sec). All six fragments start at the same time. All six records are almost identical except for 1-2 sample time lags between the neighboring channels. These time lags can be used to detect the direction to the source. This hydrophone cluster has about 100 m length; all channel sensors are placed horizontally. If the sound speed is 1500 m/sec, the time lag of the signal propagating along the antenna between two channel sensors is about 0.005 sec. If we have 300 samples per second the time lag is equal to 1.5 samples. So, the direction of this micro earthquake was detected to be directly along antenna with the angle error $\pm 18°$. All nine micro earthquakes have approximately the same direction. That means that all micro earthquake sources are localized in this $\pm 18°$-degree sector. The epicenter of the earthquake, which followed these MEQs, is also located in the same sector.

Only compression waves can propagate in liquid. So all types of seismic solid earth waves, in particular shear waves (S-waves) become compression waves when crossing the bottom. These generated compression waves in the ocean have the same phase speed independently of their origin.

So if we analyze the time difference between modified P-waves and S-waves we can determine only the distance from the source to the medium boundary (i.e. ocean bottom). For the examined event this time was very small (less than one second), so the sources of micro earthquakes had to be located not in the hypocenter zone but somewhere in the epicenter zone near the ocean bottom.

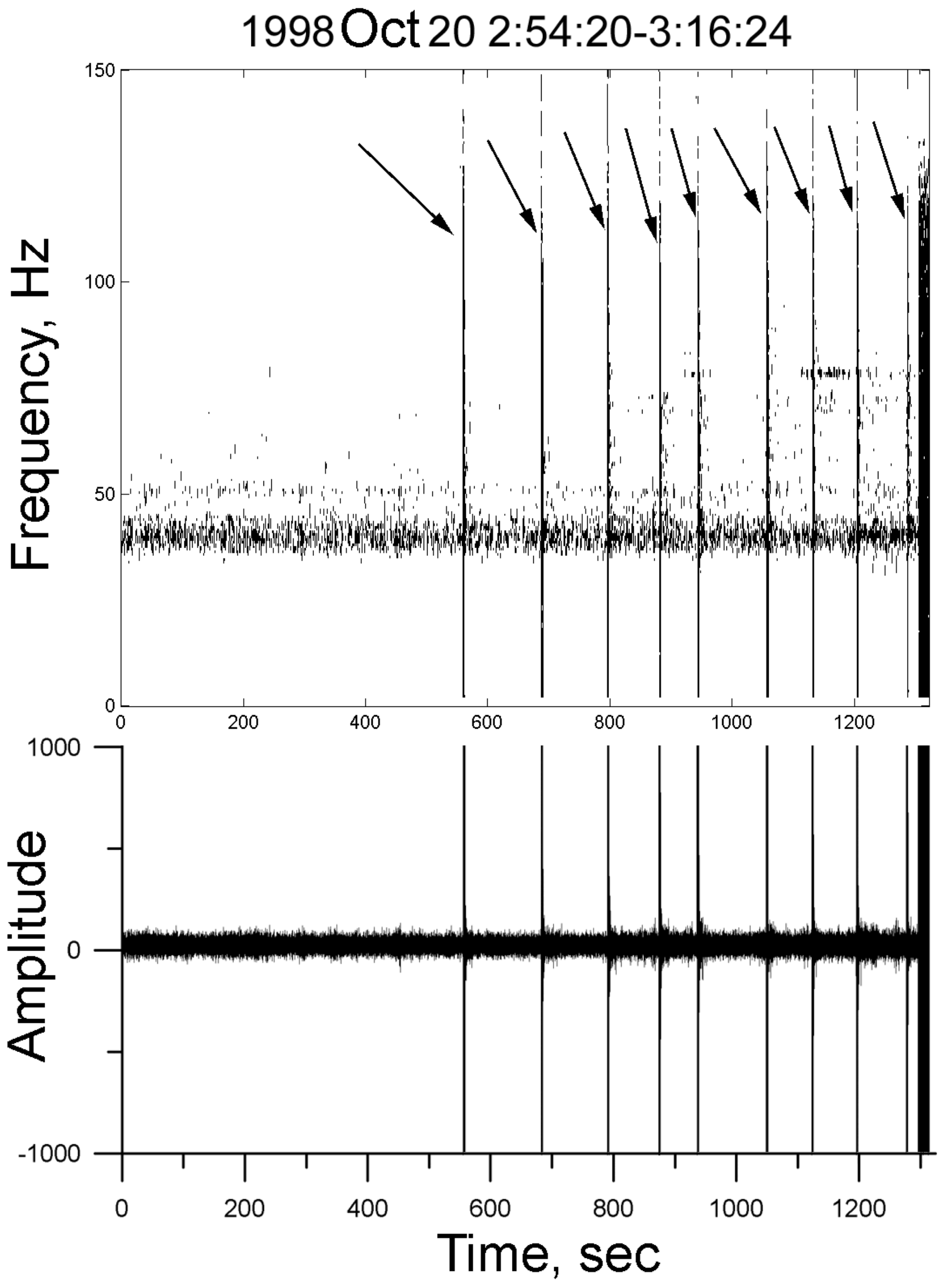

Figure 3. Hydro-acoustic record of October 20, 1998, beginning time 02:54:20 GMT, Channel #1 (b) and its spectrogram (a). Horizontal axis is time in sec, vertical axis is frequency in Hz. Arrows mark micro earthquakes.

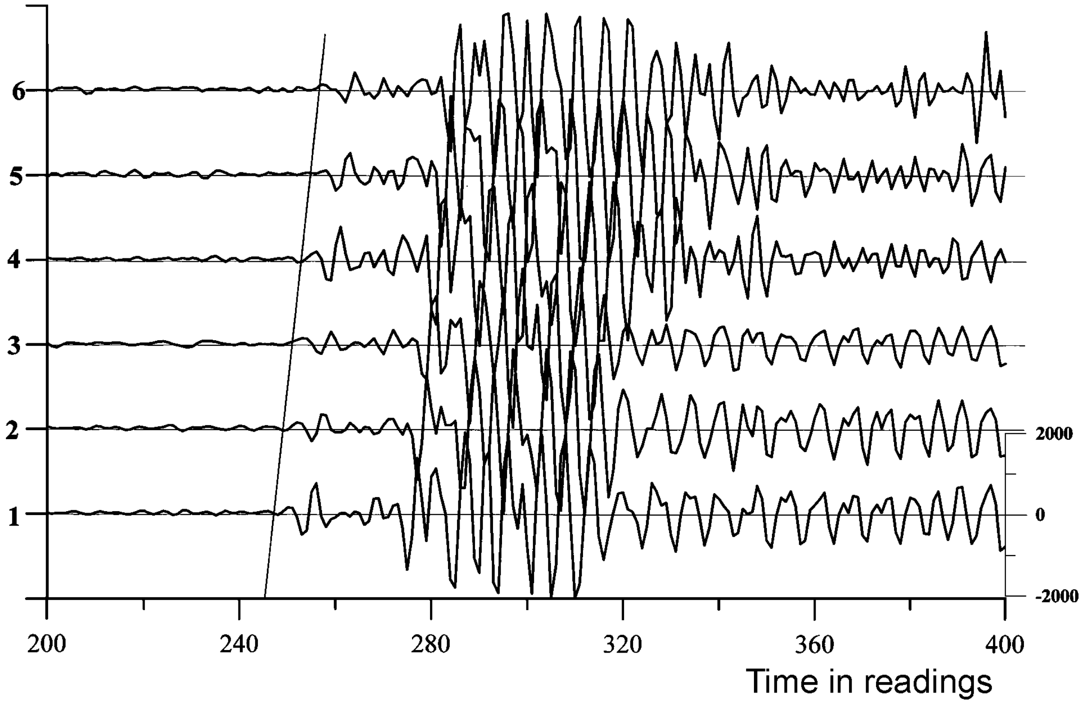

Figure 4. Simultaneous six-channel hydro-acoustic records of the micro earthquake of October 20, 1998 (02:54:20 GMT).

Table

List of seismic events in the Kamchatka region for February 5, 1999

Num.	yyyy/mm/dd	Time, hh:min:sec	Latitude, deg., N	Longitude, deg., E	Depth, km	Energe-tic class	Distance, km
1	1999 02 05	03:29:1,2	53,55	160,55	11	7,2	168,08
2	1999 02 05	12:2:55,5	55,41	162,18	35	7,0	381,41
3	1999 02 05	12:11:23,5	53,60	161,12	11	8,6	181,20
4	1999 02 05	16:37:36,8	53,25	158,62	149	7,7	122,15
5	1999 02 05	16:48:47,3	49,22	158,71	9	8,0	325,29
6	1999 02 05	19:39:54,7	52,85	159,56	55	7,2	84,08
7	1999 02 05	20:16:13,1	53,53	165,50	10	8,8	293,78
8	1999 02 05	23:46:6,1	53,61	161,27	10	8,1	184,60

On February 5, 1999 (Figure 1) 8 earthquakes occurred (see Table), and most of them were within less than 4 hours after the hydro-acoustic recording (there were six records during this day). In 12 min 37 sec after the end of the first record at 03:16:24 the first EQ occurred. There were no EQs after the second record but there were two of them in 46 min 31 sec and 56 min 59 sec after the end of the third record (10:16:24). Two more EQs occurred after the fourth record (15:16:24). Then after the fifth record (19:16:24) there were 6th and 7th EQs, first of them within 23 min 30 sec, and the second within about one hour. Finally, the 8th EQ occurred within 30 min 37 sec after the last record (23:16:24).

The spectrograms and all six records themselves are presented in Figure 5. All records except the second (6:54:20-7:16:24) were followed by one or two earthquakes and in all these five records the micro earthquakes were observed. No micro earthquakes were recorded only in the second, which was not followed by EQ.

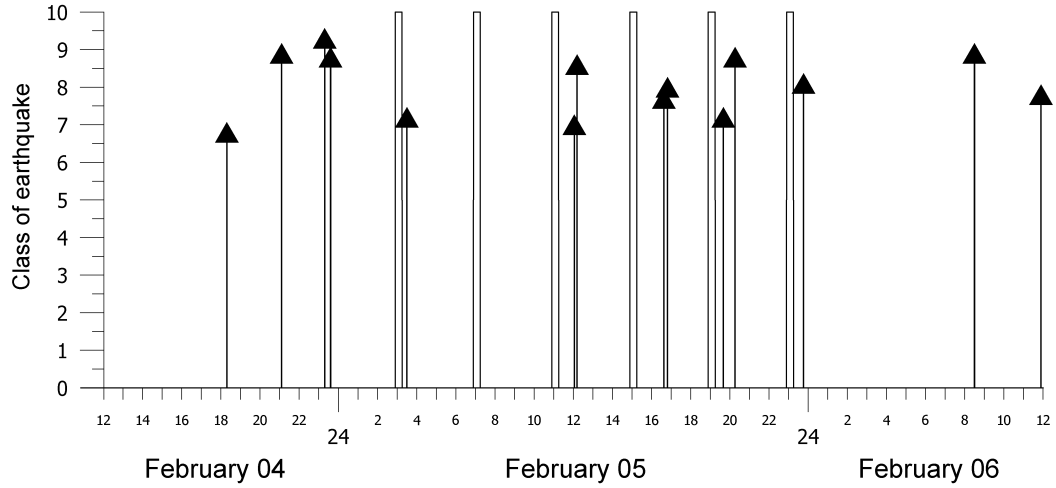

Figure 1. Earthquakes and times of the hydro-acoustic records from February 4, 1999 to February 6, 1999. Horizontal axis shows time in hours, and vertical axis presents class of the earthquake. Vertical arrows mark earthquakes from the local Kamchatka catalogue, rectangles are the times of the hydro-acoustic observations.

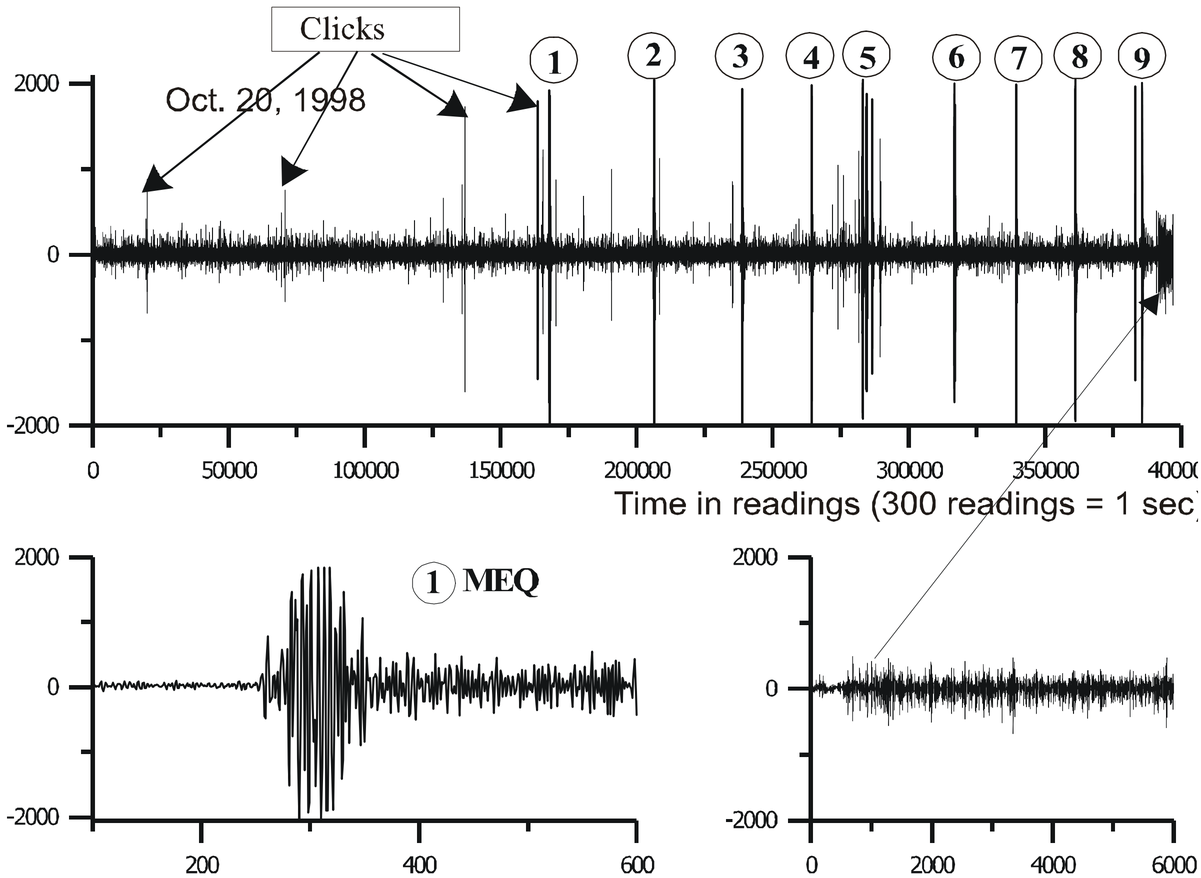

Figure 2. Hydroacoustic record of October 20, 1998, beginning time 02:54:20 GMT, Channel #14 (a) and two fragment of record: micro earthquake (b), and high frequency noise before the earthquake (c). Time in the horizontal axis is in samples (300 samples = 1 sec), vertical axis is the amplitude in mV.

Analysis of all others records give similar results. When epicenters of strong earthquakes were within more than 150 km from the antenna, the micro earthquake waveforms were different, in particular all sharp elements disappeared. For distant earthquakes (more than 300 km from the antenna) with class less than 8.5, no micro earthquakes were found.

CONCLUSIONS

Based on the combined analysis of the hydro-acoustic records and the local Kamchatka catalogue records preceding and coincident with earthquakes we found two types of signals preceding the earthquakes:

1) Series of micro earthquakes from the epicenter zone with frequency range of 40-75 Hz, occurring up to four hours before the main shock in various nearby sources.
2) The second type is the tremor occurring before the main shock (20 – 40 Hz).

Both types of signals were recorded by all antenna channels. The azimuth to the sources could be detected from the time lags.

The farther the epicenter, the smoother is the signal. If the distance is large, the P wave disappears in the background noise and only S and other waves are observed.

The hydro-acoustic records can give important information about the state of the solid earth just before the earthquake. The seismographs located inland cannot detect the respective micro earthquakes due to the significant attenuation of the signal. Thus, these records may be efficiently used for predicting local earthquakes and tsunamis.

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