Note on the Lunar-daily Distribution of Earthquakes.[1]

By

F. Omori, *Rigakushi, Rigakuhakushi,*
Member of the Imperial Earthquake Investigation Committee.

With Plates VIII and IX.

1. INTRODUCTION. The relations between earthquake frequency and the moon's position were discussed by several seismologists since the middle of the 19th century. The following is a brief summary of the more important investigations in recent years.

M. de Montessus de Ballore[2] who treated a vast earthquake catalogue, has obtained a wholly negative result. Thus, dividing the lunar day of 24 h 50 m into eight parts, of which the middle of the first corresponds to the time of the upper culmination, he finds the following earthquake distributions[3]:—

I eighth	5579 earthquakes.
II	5558
III	5611
IV	5508
V	5802
VI	5564
VII	5571
VIII	5662

1) Translation, with some additions, of an article by the Author published in the *Reports* (Japanese) of the Imp. Earthq. Inv. Com., No. 32, 1900.
2) Archives des Sciences Physiques et Naturelles, Tome XXII, 1889.
3) Trans. Seism. Soc., Vol. XV.

These figures are quoted from Dr. C. G. Knott's paper entitled: M. de Ballore's calculations on earthquake frequency[1]. He remarks that it is impossible to base any definite conclusion as to the lunar-daily periodicity in earthquakes on such numbers as these, the ratio of the maximum to the minimnm being 105 : 100.

The most important of the recent investigations on the relation between earthquake frequency and the position of the moon is that by Dr. C. G. Knott, who examined the Japan earthquakes contained in Prof. Milne's great Catalogue (Seis. Jour. of Japan, Vol. IV), and arrived, amongst others, at the following results[2]: — (1) Earthquake frequecy is subject to a periodicity associated with the lunar day; (2) The lunar half-daily period is relatively prominent, and its phase falls regularly in relation to the time of the meridian passage of the moon.

2. In the discussion of the lunar influence on earthquakes, the after shocks of a great earthquake may be supposed as furnishing the best materials for investigation, on the following two accounts:—(1) after-shocks are probably no other than the removal of the residual unstable or weak points at the disturbed tract about the focus of a great seismic disturbance, which must be particularly sensitive to the action of external agencies; (2) these shocks are mostly small local shakings whose origins are near to one another. From these considerations, I have taken, by way of trial, the after-shocks at Nagoya of the Mino-Owari earthquake of 1891, and those at Nemuro of the Hokkaido earthquake of 1894; and for the sake of comparison, ordinary earthquakes at Tokyo. The earthquake observations at Nagoya, Nemuro, and Tokyo, whose distribution in the lunar-day considered in the following §§, have all been made instrumentally by means of the Gray-Milne type seismographs.

3. LUNAR DAY. The lunar day is divided into 24 hours, the 0 hour corresponding with the moon's upper culmination for Tokyo.

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1) Trans. Seism. Soc., Vol. XV.

2) Prof. C.G. Knott: On Luner Periodicities in Earthquake Frequency. Proc. Royal Soc. London, Vol. LX, 1897.

The times of occurrence of the earthquakes at Nagoya and Nemuro, as well as those at Tokyo, have all been referred to the lunar time for the last named place. This will, however, lead to no great inaccuracy, as the longitudes at these three places are not mnch different from each other, being respectively 136° 55′, 145° 35′, and 139° 45′ *E*.

4. AFTER-SHOCKS AT NAGOYA. The great Mino-Owari earthquake took place on Oct. 28, 1891, at about 6 h 37 m a.m. The number of the after-shocks observed at the meteorological observatory of Nagoya till the end of the year 1899 was 1854. In order to avoid the effect of the rapid decrease in the seismic frequency at the commencement, let us exclude the observations within the two weeks immediately after the initial earthquake. Thus we obtain 1270 shocks for the time interval between Nov. 11, 1891, and Dec. 31, 1899, whose lunar-daily distribution is as follows.

TABLE I. LUNAR-DAILY DISTRIBUTION OF 1270 EARTHQUAKES AT *NAGOYA*.

(Nov. 11th, 1891–Dec. 31st, 1899.)

Year. / Lunar hour	1891	1892	1893	1894	1895	1896	1897	1898	1899	Sum. Hourly.	Sum. 3-hourly.
h h											
0– 1	9	7	4	8	4	8	2	3	1	46	
1– 2	11	16	2	16	9	4	0	3	0	61	174
2– 3	15	7	5	17	10	2	2	3	6	67	
3– 4	14	10	5	11	8	3	0	1	2	54	
4– 5	10	10	4	22	3	10	4	0	0	63	178
5– 6	18	11	1	12	7	1	8	0	3	61	
6– 7	14	12	4	11	2	4	3	1	1	52	
7– 8	13	9	4	14	2	3	6	3	3	57	156
8– 9	10	8	5	11	4	3	2	2	2	47	
9–10	4	8	6	11	4	6	3	3	4	49	
10–11	5	14	6	14	11	0	1	0	1	52	148
11–12	7	8	6	9	9	3	3	1	1	47	
12–13	8	9	11	14	5	6	5	3	2	63	
13–14	14	9	2	13	5	3	1	1	0	48	162
14–15	10	5	2	14	2	7	4	3	4	51	
15–16	8	7	5	6	11	12	5	1	2	57	
16–17	15	7	10	6	9	6	5	1	1	60	168
17–18	9	7	7	8	5	7	3	3	2	51	
18–19	11	5	4	15	3	3	1	4	0	46	
19–20	10	6	2	9	3	4	1	0	3	38	143
20–21	18	7	8	9	6	3	4	2	2	59	
21–22	13	9	2	9	7	1	0	2	1	44	
22–23	14	5	3	16	7	4	0	1	1	51	141
23–34	19	0	9	1	7	6	2	1	1	46	
Sum.	279	196	117	276	143	109	65	42	43	1270	
									Mean	53	159

The results in Table I are illustrated in figs. 1 and 4, x being the time and y the corresponding hourly number of earthquakes.[1)]

Hourly distribution. The principal maximum and minimum hourly

1) The curve is drown free-hand through the mean positions of every two successive points representing the relation between x and y. This method of curve drawing has been used in the case of the other diagrams.

numbers of 67 and 38 occurred respectively between the 2nd and 3rd hours, and between the 19th and 20th hours:

Greatest hourly earthquake number $=a=67$;
Smallest ,, ,, ,, $=b=38$;
Mean ,, ,, ,, $=c=53$;
$a-b=d=29$;
$\frac{d}{c}=e=55\%$.

The second maximum $(=63)$ and minimum $(=47)$ occurred respectively between the 12th and 13th hours, and between the 8th and 9th hours.

3-Hourly distribution. The curve, which is drawn by taking the earthquake numbers every 3 hours (fig. 4), indicates clearly two maxima and two minima. The principal maximum and minimum numbers of 178 and 141 occurred respectively between the 3rd and 6th hours and between the 21st and 24th hours:—

Greatest 3-hourly earthquake number $=A=178$;
Smallest ,, ,, ,, $=B=141$;
Mean ,, ,, ,, $=C=159$;
$A-B=D=37$;
$\frac{D}{C}=E=23\%$.

The 2nd maximum $(=168)$ and minimum $(=148)$ occurred respectively between the 15th and 18th hours, and between the 9th and 12th hours.

The symbols a, b, c, d, e, A, B, C, D, E, have in the cases of Nemuro and Tokyo earthquakes considered next the same meaning as in the present §.

5. NEMURO AFTER-SHOCKS. The Hokkaido earthquake took place on March 22, 1894, at 7h 56m p.m. The after-shocks recorded at the Meteorological Observatory of Nemuro till the end of 1899 was 1057. Excluding the shocks which happened during the first three days, to avoid the effect of the rapid decrease at the commencement, there were

in the time interval between March 25th, 1894, and Dec. 31st, 1899, 799 earthquakes, whose lunar-daily distribution is as in Table II.

TABLE II. LUNAR-DAILY DISTRIBUTION OF 799 EARTHQUAKES AT *NEMURO*.

(March 25th, 1894—Dec. 31st, 1899.)

Year. / Lunar hour	1894	1895	1896	1897	1898	1899	Sum.	
							Hourly.	3-hourly.
h h								
0– 1	21	8	4	2	2	0	37	
1– 2	20	8	7	2	1	2	40	106
2– 3	18	1	1	2	2	5	29	
3– 4	20	7	4	2	1	5	39	
4– 5	25	8	5	5	2	2	47	117
5– 6	18	6	1	2	2	2	31	
6– 7	17	7	5	2	5	4	40	
7– 8	11	2	4	1	1	1	20	92
8– 9	17	7	3	3	1	1	32	
9–10	14	4	2	5	3	3	31	
10–11	17	7	5	4	1	1	35	98
11–12	21	3	4	2	1	1	32	
12–13	17	10	3	4	4	1	39	
13–14	23	4	5	2	1	1	36	107
14–15	14	7	2	2	2	5	32	
15–16	21	5	3	2	1	4	36	
16–17	14	4	2	3	3	3	29	95
17–18	17	2	4	4	1	2	30	
18–19	19	5	7	1	0	1	33	
19–20	16	4	1	4	3	7	35	98
20–21	25	1	2	1	0	1	30	
21–22	17	9	3	4	0	3	36	
22–23	9	2	2	3	2	3	21	86
23–24	12	6	4	0	3	4	29	
Sum.	423	127	83	62	42	62	799	

Mean........33....100

Hourly distribution. According to fig. 2, the principal maximum and minimum hourly numbers of 47 and 20 occurred respectively between the 4th and 5th hours, and between the 7th and 8th hours:

$$a=47 \text{ earthquakes.}$$
$$b=20 \quad ,,$$
$$c=33 \quad ,,$$
$$a-b=d=27 \quad ,,$$
$$\frac{d}{c}=e=82 \%$$

The 2nd maximum and minimum of 39 and 21 occurred respectively between the 12th and 13th hours, and between the 22nd and 23rd hours.

3-Hourly distribution. According to fig. 5, which shows the 3-hourly distribution of the earthquakes, there were two maxima and two minima. The principal maximum and minimum numbers of 117 and 86 occurred respectively between the 3rd and 6th hours, and between the 21st and 24th hours:—

$$A=117 \text{ earthquakes.}$$
$$B=86 \quad ,,$$
$$C=100 \quad ,,$$
$$A-B=D=31 \quad ,,$$
$$\frac{D}{C}=E=31 \%.$$

The 2nd maximum and minimum of 107 and 92 occurred respectively between the 12th and 15th hours, and between the 6th and 9th hours.

6. TOKYO EARTHQUAKES. The lunar-daily distribution of the 1462 earthquakes observed at the Central Meteorological Observatory during the 12 years between Jan. 1888 and Dec. 1899 is given nii Table III.

TABLE III. LUNAR-DAILY DISTRIBUTION OF 1462 EARTHQUAKES AT TOKYO.

(Jan. 1888—Dec. 1899.)

Lunar hour. \ year	1888	1889	1890	1891	1892	1893	1894	1895	1896	1897	1898	1899	Sum. Hourly.	Sum. 3-hourly.
h h														
0— 1	4	3	6	7	4	2	9	9	13	7	5	2	71	
1— 2	4	4	2	5	6	4	1	10	6	5	5	4	56	190
2— 3	4	6	7	3	4	3	2	5	10	7	4	8	63	
3— 4	6	5	1	4	6	3	6	3	9	4	5	6	58	
4— 5	6	5	4	4	2	0	7	4	9	14	9	4	68	184
5— 6	3	3	5	3	3	3	3	4	12	5	4	10	58	
6— 7	2	9	8	6	5	3	6	4	9	8	6	2	68	
7— 8	8	8	3	4	7	3	3	5	5	4	8	3	61	185
8— 9	3	4	3	4	4	3	3	5	9	2	8	8	56	
9—10	3	2	5	4	5	1	4	5	8	8	10	4	59	
10—11	2	2	4	6	4	1	4	5	13	7	6	1	55	167
11—12	5	3	4	6	2	3	4	2	8	7	5	4	53	
12—13	4	7	3	7	7	6	6	5	9	5	9	4	72	
13—14	3	8	3	3	3	0	3	5	10	5	8	3	54	189
14—15	6	3	2	5	2	4	5	5	10	9	7	5	63	
15—16	5	4	7	7	4	0	4	6	12	11	7	4	71	
16—17	4	5	2	3	3	1	1	4	4	10	3	6	46	186
17—18	4	9	1	5	5	4	3	4	14	6	7	7	69	
18—19	2	3	3	1	3	5	4	10	9	7	4	8	59	
19—20	7	8	6	6	3	0	5	4	11	5	5	5	65	188
20—21	5	3	3	5	3	2	6	6	8	7	8	8	64	
21—22	3	2	2	4	2	4	5	10	12	6	4	8	62	
22—23	4	5	6	7	4	2	1	4	5	4	3	8	53	173
23—24	4	2	3	14	1	4	6	7	5	5	3	4	58	
	101	113	93	123	92	61	101	131	220	158	143	126	1462	
												Mean.	61......	183

Hourly distribution. According to fig. 3, the principal maximum and minimum hourly earthquake numbers of 72 and 46 occurred respectively between the 12th and 13th hours, and between the 16th and 17th hours:—

$a = 72$ earthquakes

$b = 46$,,

$$c=61 \text{ earthquakes}$$
$$a-b=d=26 \quad ,,$$
$$\frac{d}{c}=e=43 \%$$

The 2nd maximum of 71 occurred between the 0 and 1st hours, and the 2nd minimum of 53 between the 11th and 12th hours and also between the 22nd and 23rd hours.

3-Hourly distribution. The curve of the 3-hourly distribution (fig.6) indicates clearly a 12-hours period. The maximum and minimum numbers of 190 and 167 occurred respectively between the 0 and 3rd hours, and between the 9th and 12th hours:—

$$A=190 \text{ earthquakes}$$
$$B=167 \quad ,,$$
$$C=183 \quad ,,$$
$$A-B=D=23 \quad ,,$$
$$\frac{D}{C}=E=13 \%.$$

The 2nd maximum and minimum of 189 and 173 occurred respectively between the 12th and 15th hours, and between the 21st and 24th hours.

7. SUMMARF OF RESULTS. The results obtained in the preceding three §§ may be summarized as follows.

Hourly distribution. The curves of the hourly earthquake distribution for the three places are similar to one another, each indicating two maxima, of which the 1st occurred between the 0 and 5th hours, and of which the 2nd occurred in all the three cases between the 12th and 13th hours. In the case of the Tokyo earthquakes the two maxima were nearly equal to one another; while in the cases of Nagoya and Nemuro earthquakes, the 1st maximum was somewhat greater than the 2nd. The occurrence of the two seismic maxima, at a mean interval of 12 hours, and approximately at, or a little after, the meridian passages of the moon, may probably be due to the stress in the earth's crust caused by the direct attraction of the moon.

The dotted lines in figs. 1, 2 and 3, showing the mean variation of the earthquake frequency, indicate in each case, two maxima, of which the 1st occurred between the 7th and 12th hours, and the 2nd between the 19th and 23rd hours.

It is hereby to be remarked that almost the total number of the earthquakes at Nemuro and Nagoya were small local shocks, whose origins were, in the two cases, totally different. Further, the Nemuro earthquakes were entirely of submarine origin, and Nagoya earthquakes mostly of inland origin; while the Tokyo earthquakes, whose origins were different from those at the two above places, were partly submarine and partly inland. Notwithstanding these differences in the origins of earthquakes the lunar-daily distribution of earthquakes at the three places were alike to one another. The values of *c*, or the amount of fluctuation of the hourly number of earthquakes, for Nagoya, Nemuro, and Tokyo, were respectively 55, 82, and 43%, giving an average of 60%.

8. TIDES. The relation between earthquakes and the position of the moon must be a complicated one, as, besides the direct stress caused by the moon in the earth's crust, there we have also to deal with the effect of the tides, for which the times of high and low waters are considerably different in various portions of the coasts of the Japanese Islands. At Reigan-jima, Tokyo, the high water occurs from 5 h to 6 h 20 m after the meridian passage of the moon. The times of the high water at some places along the Pacific and Japan sea coasts, referred to that at Reigan-jima, are as in the following table; being positive (+) when additive, and negative (−) when subtractive.

Place.	Time of High water.	Place.	Time of High water.
Kuwana.	+0h 37m	Yokohama.	−0h 01m
Hyogo.	+1 34	Ishinomaki.	−1 16
Osaka.	+2 01	Hakodate.	−1 03
Shimonoseki.	+3 06	Niigata.	−3 01
Nagasaki.	+1 56	Fushiki.	−2 57

From the above table, it will be seen that the times of the high water at the different places on the Japanese coasts are 2 to 9½ hours after the meridian passage of the moon. The fluctuations in the seismic frequency shown in figs. 1, 2, and 3, may entirely, or partly, be due to the tidal motion of sea waters. (See also § 9.)

9. *3-Hourly variation.* The curves of the 3-hourly seismic variation at the three places (figs. 4, 5, and 6) are approximately identical with one another, each indicating two maxima and two minima. The two maxima occurred respectively between the 0 and 6th hours, and between the 12th and 18th hours; the 1st maximum being somewhat greater than the 2nd. The two minima occurred respectively between the 6th and 12th hours, and between the 21st and 24th hours. The values of the ratio E, or the amount of the fluctuation of the 3-hourly seismic frequency, were for Nagoya, Nemuro and Tokyo, respectively 23, 31, and 13%, giving an average of 22%.

10. The conclusions above obtained for the three places of Nagoya, Nemuro and Tokyo, may be different from those for other places. It is, for instance, quite possible that for some places the lunar-daily distribution of earthquakes indicates only a single maximum and a single minimum. The discussion of earthquakes observed at Gifu, Kumamoto, Kagoshima, Ishinomaki, Utsunomiya, etc., will form the subject of another note.

11. COMPARISON OF THE LUNAR AND BAROMETRIC EFFECTS ON THE SEISMIC FREQUENCY. Let us compare the lunar effect discussed above with the effect of the barometric pressure on the diurnal seismic frequency at the same three places. In the *Publications*, No. 8, there ar tables showing diurnal distributions of 1851, 991, and 2208 earthquakes observed at Nagoya, Nemuro and Tokyo respectively. From these tables, as well as from those given in §§ 4, 5 and 6, I have constructed the following, showing for each place the excess of the different hourly earthquake numbers over the least.

TABLE IV. LUNAR-DAILY AND DIURNAL VARIATIONS OF SEISMIC FREQUENCY.

Lunar hour.	MOON'S EFFECT. (Lunar-daily seismic variation.)					Hour.	BAROMETRIC EFFECT. (Diurnal seismic variation.)				
	Nagoya.	Nemuro.	Tokyo.	Sum.	Sum—Minimum.		Nagoya.	Nemuro	Tokyo.	Sum.	Sum—Minimum.
						a.m.					
0— 1	46	37	71	154	29	0— 1	99	39	92	233	64
1— 2	61	40	56	157	32	1— 2	117	40	81	238	72
2— 3	67	29	63	159	34	2— 3	96	40	90	226	60
3— 4	54	39	58	151	26	3— 4	101	50	85	236	70
4— 5	63	47	68	178	53	4— 5	103	50	71	224	58
5— 6	61	31	58	150	25	5— 6	82	48	87	217	51
6— 7	52	40	68	160	35	6— 7	61	44	95	200	34
7— 8	57	20	61	138	13	7— 8	60	50	92	202	36
8— 9	47	32	56	135	10	8— 9	82	44	96	222	56
9—10	49	31	59	139	14	9—10	67	37	113	217	51
10—11	52	35	55	142	17	10—11	57	43	93	193	27
11—12	47	32	53	132	7	11—12	82	53	84	219	53
						p.m.					
12—13	63	39	72	174	49	0— 1	55	41	79	175	9
13—14	48	36	54	138	13	1— 2	79	26	91	196	30
14—15	51	32	63	146	21	2— 3	56	25	85	166	0
15—16	57	36	71	164	39	3— 4	72	45	104	221	55
16—17	60	29	46	135	10	4— 5	65	44	97	206	40
17—18	51	30	69	150	25	5— 6	78	42	81	201	35
18—19	46	33	59	138	13	6— 7	55	38	89	182	16
19—20	38	35	65	138	13	7— 8	75	43	93	211	45
20—21	59	30	64	153	28	8— 9	67	41	104	212	46
21—22	44	36	62	142	17	9—10	79	41	100	220	54
22—23	51	21	53	125	0	10—11	85	30	107	222	56
23—24	46	29	58	133	8	11—12	81	37	99	217	51
Sum	1270	799	1462	3531	531	Sum	1854	991	2208	5053	1069

Let N, S, S_1, and S_2 denote, for the lunar-daily distribution, the following quantities:—

N = Hourly number of earthquakes;

S = Total earthquake number;

$S_1 = 24 \times b$;

$S_2 = \Sigma(N-b) = S - S_1$;

b denoting the minimum hourly earthquake number, as in §§ 4, 5 and 6. Further let the symbols b', N', S', S_1', and S_2' denote the corresponding quantities for the diurnal distribution of earthquakes. Then the results contained in the above table may be summarized as in the two following ones.

Lunar-daily Earthquake Distribution.

Place.	S	$S_1 = 24 \times b$.	$S_2 = S - S_1$	Ratio, $\frac{S_2}{S_1}$	Ratio, $\frac{S_2}{S}$
Nagoya.	1270	912	358	0.39	0.28
Nemuro.	799	480	319	0.66	0.40
Tokyo.	1462	1104	358	0.33	0.25
3 places taken together.	3531	3000	531	(mean) 0.46	(mean) 0.31

Diurnal Earthquake Distribution.

Place.	S'	$S_1' = 24 \times b'$.	$S_2' = S' - S_1'$	Ratio, $\frac{S_2'}{S_1'}$	Ratio, $\frac{S_2'}{S'}$
Nagoya.	1854	1320	534	0.40	0.29
Nemuro.	991	600	391	0.65	0.39
Tokyo.	2208	1704	504	0.30	0.23
3 places taken together.	5053	3984	1069	(mean) 0.45	(mean) 0.30

From the above two tables, we see that, for each of the three places, the ratios $\frac{S_2}{S_1}$ and $\frac{S_2}{S}$ are very nearly equal respectively to the ratios $\frac{S_2'}{S_1'}$ and $\frac{S_2'}{S'}$, which shows that in the diurnal and lunar-daily seismic variations the moon's effect is approximately equal to that of the barometric pressure. This fact admits of a simple explanation, provided the *lunar effect* be considered not as the effect of the moon's direct attraction, but as the effect due to the weight of the sea waters in the tidal motion. Thus, according to my note on the annual variation of the height of sea-level,[1] the total change of pressure at the sea bottom off the Pacific coast of the Main Island seems to be opposite in sense, but equal in amount, to that of the barometric pressure on land.

The numbers S_2 and S_2', which may be assumed respectively as the aggregate amount of the lunar and barometric effects on the lunar-daily and diurnal seismic variations are as follows:

For Nagoya: $S_2+S_2'=28+29=57$ %
,, Nemuro: ,, $=40+39=79$,,
,, Tokyo; ,, $=25+23=48$,,

It thus seems that a considerable proportion of earthquakes, from some 50 to 80 %, are caused, or accelerated to occur, by the agencies of the atmospheric pressure and the moon's influence or tidal stress.

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1) This volume, pp. 24–26.

Lunar-daily distribution of Earthquakes.

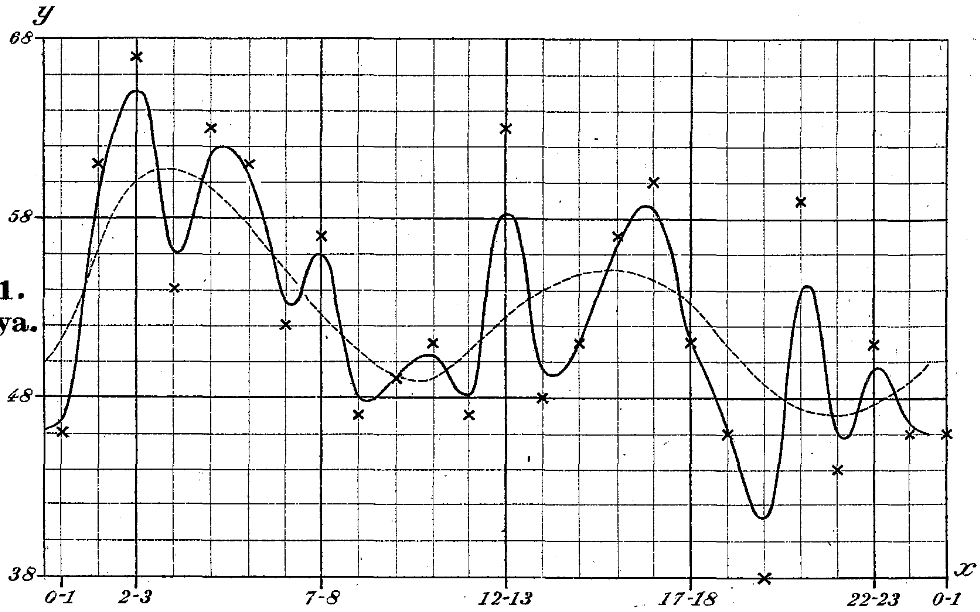


Fig. 1.
Nagoya.

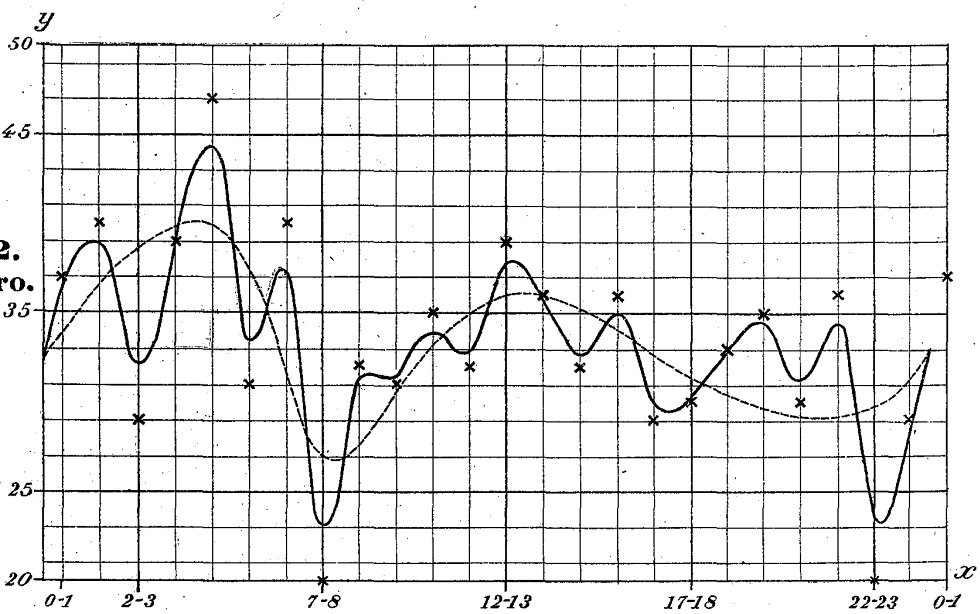


Fig. 2.
Nemuro.

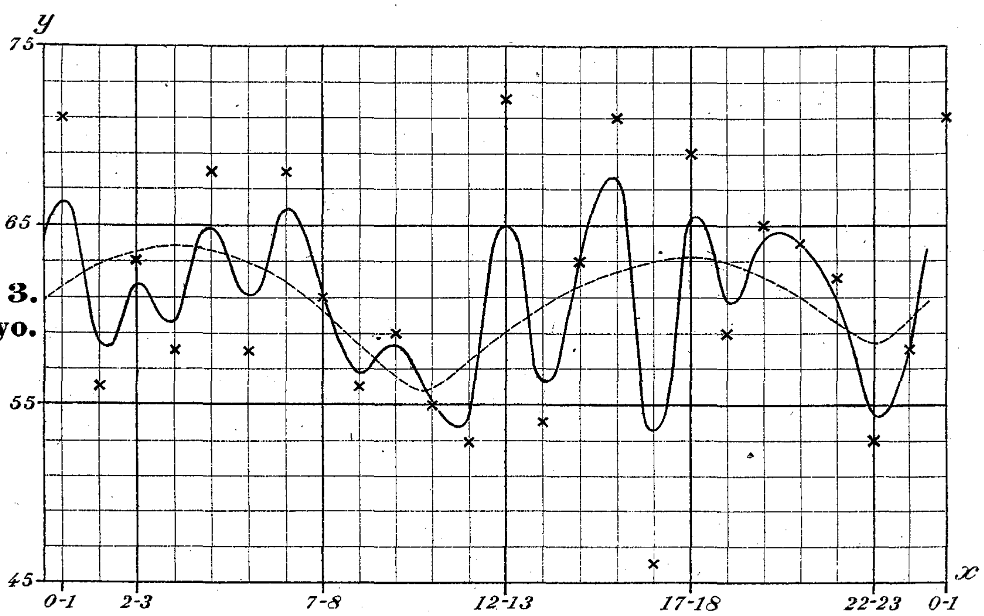


Fig. 3.
Tokyo.

x=Time (lunar hour).

y=Hourly (lunar) number of earthquakes.

Lunar-daily distribution of Earthquakes.

Fig. 4.
Nagoya.

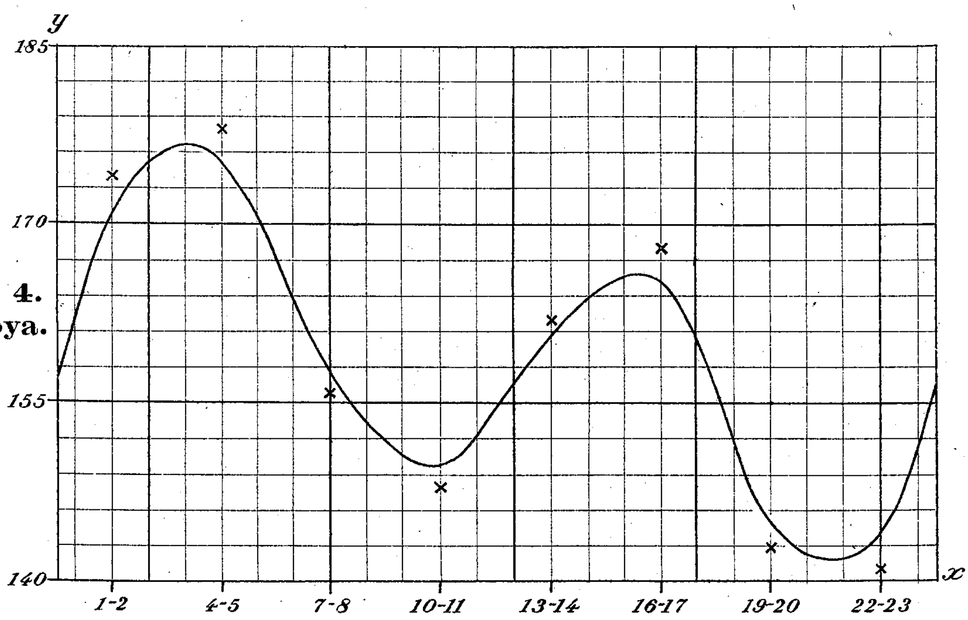


Fig. 5.
Nemuro.

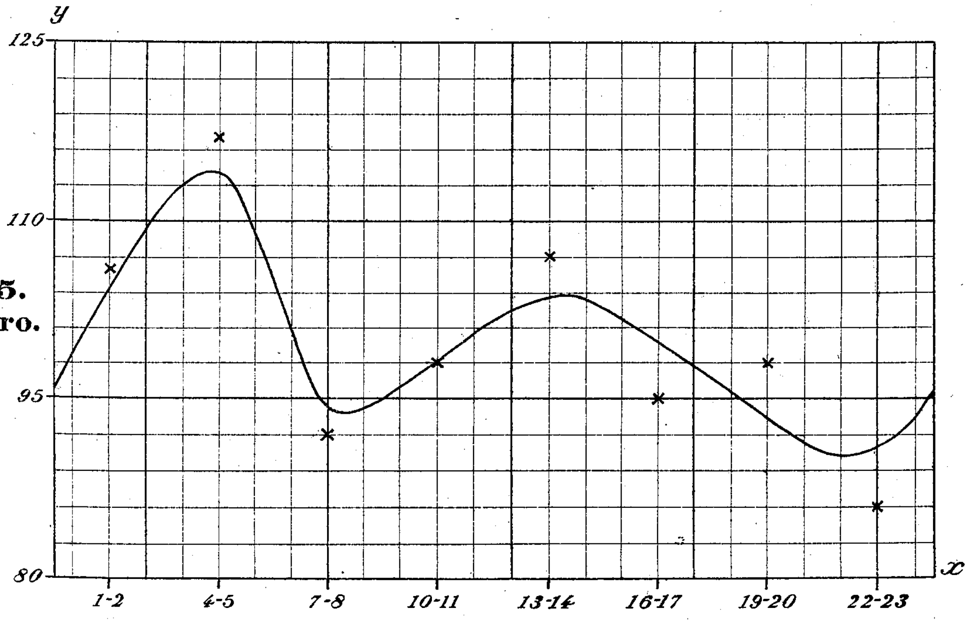
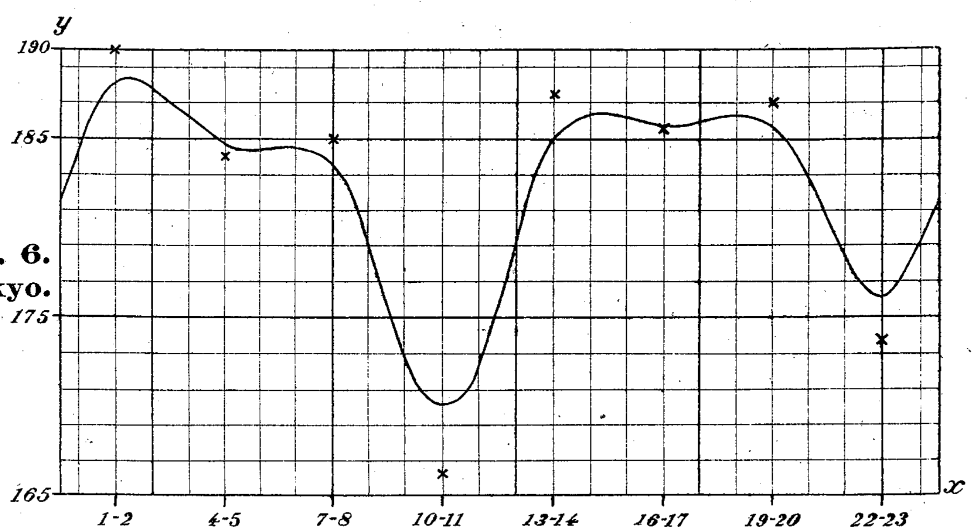


Fig. 6.
Tokyo.



x = Time (lunar hour).

y = 3-hourly (lunar) number of earthquakes.