JOURNAL OF THE COLLEGE OF SCIENCE, TOKYO IMPERIAL UNIVERSITY.
VOL. XXXVII., ARTICLE 4.

On the Distribution of Cyclonic Precipitation in Japan.

(Contribution I. from the Geophysical Seminary in the Physical Institute, College of Science).

By

Torahiko TERADA,
Rigakuhakushi,

Takezô YOKOTA, *Rigakushi.* and **Syôhu OTUKI,** *Rigakushi.*

The distribution of cyclonic precipitations has been investigated by many meteorologists for different localities. H. Hildebrandsson[1.] found that in Upsala, the precipitation is most abundant on the W side of a depression. Åkerblom[2.] found the heaviest rainfall in Thorshavn on the front right quadrant of a centre, whereas in Vienna it was on the opposite side. Since these classical investigations, it seems to have been a favourite problem to inquire on which side of a depression the precipitation is most frequent or abundant. Krankenhagen[3.] found greatest precipitation in Swinemünde on the rear side of a cyclone and attributed the fact to the influence of seawind prevailing on that side. V. Drapczyanski[4.] came to the conclusion that the precipitation in St. Louis, U.S.A., is most frequent on the rear side, but the average amount of rain on raindays most abundant on the S side. H. R. Mill[5.] investigated the trace or "smear" swept by the rain area accompanying a number of remarkable depressions passing over Great Britain, and came to the result that "the belt of cyclonic rains is much wider on the left

---

1.) H. Hildebrandsson, Sur la distribution des éléments mét. autour des minima et des maxima barométriques, Upsala 1883; v. Bebber, Met. ZS., 1884.

2.) Ph. Åkerblom, Sur la distribution à Vienne et à Thorshavn des éléments etc.

3.) Krankenhagen, Met. ZS. 1885. See also Polis, Met. ZS., 1904.

4.) Drapczyanski, Met. ZS. 1903.

5.) H. R. Mill, Symon's Met. Mag. **39**, 1904; Quart. Journ. R. Met. Soc. **36**, 1908.

of the path than on the right, and the heaviest falls occur in advance of the centre" regardless of the direction of progression of the depression. He also remarks that the distribution of cyclonic rains seems to have no apparent relation to the physical feature of the country, though data were wanting to decide the point. J. A. Udden(1.) who attacked the problem for Davonport, Rock Island, Ill., U.S.A. and also for a number of other districts, found that the position of the area of the greatest rainfall-frequency relative to the depression, varies largely for different localities ; he suggested that the relation may vary with the hours, the seasons and the courses taken by the depression. W. G. Reed(2.), following the method adopted by Mill, made an extensive investigation of the "smear" for a number of cyclones passing over the U.S.A. His results are not so simple as that of Mill. He notes rightly the considerable influence of large water bodies, such as the Atlantic Ocean and the Great Lakes and also the fact that the rain area forms a series of patches, the heavier ones being connected by lighter ones or rainless areas. The latter fact is also attributed to the influence of important water bodies, though he concludes : "every relation expected occurs, but there seems to be as yet no classification which will reduce the relation to a system." Hann(3.) discusses these results in his Lehrbuch and emphasizes the influence of the districts over which the wind comes.

One of the authors(4.) has discussed the influence of the distribution of land and water in modifying the meteorological feature of a region and proposed a simple theory which may explain many regional irregularities of barometric distribution. As an illustration of this theory, he drew attention to the difference of the Pacific and Japan Sea Coasts, with regard to the relative position of the rain area and the centre of barometric depression. The present paper may be regarded on one hand as the continuation of the above cited one, in so far as the results of the statistical investigation are reviewed under the light of the theory, but on the other hand as a contribution to the literature on the general precipitation problem.

1.) J. A. Udden, Symon's Met. Mag. **41**, 1906.
2.) W. G, Reed, Monthly Weather Review, Oct. 1911.
3.) Hann, Lehrbuch d. Met. 3te Auf. S. 524, 552.
4.) Terada, Proc. Tôkyô Math.-Phys. Soc, **7**, 1914.

Method of Investigation.

The "smear" method adopted by Mill and Reed, though very useful and convincing for its proper purpose, is not convenient for revealing the influence of the physical nature of land, since this effect essentially lies in the peculiar distribution of precipitation determined by the momentary position of the given configuration of land and water, or of flat land and mountain range, relative to the centre of depression, and may be quite obliterated if only the smear is compared with the track of the centre. To make the effect apparent, it is necessary to find the probability or the amount of precipitation at different districts for different positions of the depression. If these statistical data be at hand, we may construct the isohyets for the different positions of the depression, or draw for each district a diagram showing the distribution of the probability or the amount for the different positions of the centre relative to the district in question.

As material for the present statistical investigations the daily weather charts and "Kisyôyôran" (a brief monthly weather review) of the Central Meteorological Observatory, from January 1905 to December 1915 were used. The different districts of which the precipitations were to be investigated were at first classified into three groups: Pacific, Japan Sea and middle regions. Each group was again divided into six subgroups including the meteorological stations mentioned below:

P_1 Kagosima, Satazaki, Toizaki, Miyazaki.
P_2 Asizuri, Kôti, Hinomisaki, Siomisaki.
P_3 Namikiri, Tu, Nagoya, Hamamatu.
P_4 Numadu, Nagaturo, Yokosuka, Yokohama, Tôkyô, Mera, Tyôsi, Mito, Tukuba.
P_5 Kanayama, Kinkwazan, Isinomaki, Miyako.
P_6 Tokati, Kusiro, Nemuro, Abasiri.
M_1 Ôita, Matuyama, Hirosima, Kure.
M_2 Okayama, Tadotu, Tokusima, Wakayama, Kôbe, Ôsaka, Yagi.

M_3 Gihu, Iida, Kôhu, Takayama, Matumoto, Nagano.
M_4 Kumagaya, Maebasi, Asio, Utunomiya.
M_5 Hukusima, Yamagata, Midusawa.
M_6 Aomori, Tappi, Hakodate.
J_1 Kumamoto, Nagasaki, Saseho, Saga, Hukuoka, Simonoseki.
J_2 Hamada, Sakai.
J_3 Kyôgasaki, Maiduru, Kyôto, Hikone, Hukui.
J_4 Kanazawa, Husiki, Minatuki, Niigata.
J_5 Kamo, Akita.
J_6 Suttu, Sapporo, Kamikawa, Sôya.

The above order of grouping may appear somewhat arbitrary and be liable to the objection that it takes no account of the peculiar local climatic or physical features. This may, however, be justified if we consider that the principal aim of the present investigation is to sort out the general influence of the configuration of land and water with respect to the centre of depression. Korea, Saghaline and Formosa were excluded, since these regions may obviously stand under the influence of depressions existing beyond the limit of the weather chart.

The position of the centre of depression was determined not only by the daily chart, but also by consulting the chart of the track of depressions given in "Kisyôyôran." The chart area was divided into 2.5° square meshes and the position of the centre was fixed within one of these meshes.

Our first procedure was to examine the daily charts one by one and for each position of the centre to note down the districts with or without precipitation. Here we met of course with a difficulty. In many cases more than one centre appeared in the chart, to say nothing of the supposed shallow depressions appearing side by side, especially in days with generally small barometric gradient all over the chart area. In such a case, we are liable to an arbitrary prejudice in discriminating whether the precipitation in a given district was due to the one or the other of the coexisting depressions. Again, when an extensive depression is bifurcated, as is often the case when it is crossing over the main island, we cannot fix the position of the "effective" centre, without making more or less uncertain assumptions. Since it was our immediate purpose to investigate the distribution for an isolated simple depression and discuss the results from the theoretical standpoint, all these ambiguous cases were excluded, confining our attention only to the simplest cases where only one conspicuous depression is shown in the chart.* It must be admitted that in adopting this selection, we are taking only those precipitations in consideration which correspond to a quite limited weather type, and hence that the whole subsequent discussion has no reference to the cases of precipitations of noncyclonic type. Again, since each district includes a number of stations, it occurs as a rule that for each position of the centre, many districts have only partial rain or snow. Those cases with precipitation in only one station, but with none in the others, were counted as "no precipitation," otherwise as "precipitation" for that district. It must be remarked that the hours to which the weather charts refer are limited to 6a, 2p, 10p, while the distribution of precipitation in other hours may often vary widely. But for the present investigation, the three observations in a day seem to be more than sufficient. Finally it must be remarked that the cases in which there exists a centre of depression in the chart, but with no precipitation in either station, were excluded. Such a case, which is only met with when the centre is near the margin of the chart, is rather rare and the corresponding position of the centre more or less doubtful. At any rate, the weight of these extreme positions for the result is small and must be taken into consideration, if at all, with precaution.

The statistical part of the investigations was chiefly carried out by Yokota and Ôtuki. The number of times n in which the "precipitation" occurred in a given district, say P_1, corresponding to a given position of the depression, say A, divided by the number of times N in which the centre was found in the area A, expressed in percent, was called the "expectation" of precipitation for the pair (P_1, A). The result of the statistical part is shown in Table I. The first column gives the positions of the centre of

---

* In such cases, the position of the centre could be determined with a fair degree of certainty.

depression ; all those positions of which the total number *N* was less than 5 were excluded. The second column gives the number *N*. The remaining columns give the percentage expectation *n*/*N*%, for each district named at the head.

TABLE I.

Position of Centre.		*N*	P_1	P_2	P_3	P_4	P_5	P_6	M_1	M_2	M_3	M_4	M_5	M_6	J_1	J_2	J_3	J_4	J_5	J_6
22°.5- 25° 122.5-125	N E	10	70	40	0	30	0	0	60	0	20	20	0	0	40	20	10	0	0	0
,, ,, 125 -127.5	N E	7	67	71	30	33	0	0	33	40	14	14	0	0	50	33	0	0	0	0
,, ,, 127.5-130	N E	9	33	44	33	22	0	0	33	29	0	0	0	0	33	11	0	0	0	0
25 - 27.5 125 -127.5	N E	18	0	39	0	28	0	0	39	28	22	11	17	0	56	33	28	11	6	0
,, ,, 127.5-130	N E	18	56	44	28	45	0	0	17	7	28	22	11	0	44	17	11	22	6	0
,, ,, 130 -132.5	N E	9	56	78	28	33	0	0	44	17	45	22	0	11	22	55	55	33	11	0
27.5- 30 125 -127.5	N E	13	0	23	15	15	0	0	38	15	8	8	4	0	46	23	15	15	0	0
,, ,, 127.5-130	N E	28	62	43	14	11	0	0	43	36	14	4	11	0	57	36	14	11	0	0
,, ,, 130 -132.5	N E	19	64	47	47	47	5	0	63	52	37	42	8	0	53	47	41	26	0	0
,, ,, 132.5-135	N E	12	58	50	25	42	8	0	42	33	17	25	0	0	33	33	8	14	0	0
30 - 32.5 122.5-125	N E	5	0	0	0	0	0	0	0	0	0	0	0	0	80	0	0	0	0	0
,, ,, 125 -127.5	N E	19	60	32	5	5	0	0	42	26	0	0	0	0	74	26	10	5	0	0
,, ,, 127.5-130	N E	24	37	75	21	17	4	0	67	50	17	8	0	0	71	54	21	16	7	4
,, ,, 130 -132.5	N E	30	71	76	54	27	3	0	73	70	32	19	0	0	78	65	38	24	3	0
,, ,, 132.5-135	N E	37	76	87	73	43	16	5	62	81	68	32	14	3	49	70	73	41	14	0
,, ,, 135 -137.5	N E	37	22	48	87	84	24	8	24	49	65	62	27	11	16	22	49	49	11	3
,, ,, 137.5-140	N E	22	11	18	59	77	37	0	13	23	55	59	32	14	23	23	32	32	9	0
,, ,, 140 -142.5	N E	12	5	0	25	84	25	0	0	18	42	50	33	17	8	42	42	42	25	8
32.5- 35 122.5-125	N E	8	75	50	38	0	0	0	38	0	0	0	0	0	75	25	0	0	0	0
,, ,, 125 -127.5	N E	12	66	58	25	8	0	0	67	58	9	0	0	0	92	75	17	8	0	0
,, ,, 127.5-130	N E	24	50	67	35	8	0	0	62	54	38	13	4	0	83	71	50	21	0	0

Position of Centre		*N*	P_1	P_2	P_3	P_4	P_5	P_6	M_1	M_2	M_3	M_4	M_5	M_6	J_1	J_2	J_3	J_4	J_5	J_6
32.5°–35° 130 –132.5	N E	21	62	76	48	43	5	0	41	59	57	38	14	0	67	67	62	43	0	0
,, ,, 132.5–135	N E	24	13	72	63	58	38	0	54	79	71	58	29	13	58	75	75	54	21	4
,, ,, 135 –137.5	N E	24	8	50	79	79	46	8	25	58	83	67	33	12	25	59	75	67	42	13
,, ,, 137.5–140	N E	28	4	25	47	90	39	7	71	25	50	68	25	14	14	14	57	39	11	36
,, ,, 140 –142.5	N E	27	4	0	15	74	56	11	0	7	37	44	29	7	7	19	33	51	45	7
35 – 37.5 125 –127.5	N E	16	31	50	13	6	6	0	50	50	19	12	6	0	62	31	25	19	13	0
,, ,, 127.5–130	N E	7	35	57	43	43	14	0	72	43	43	19	14	0	86	86	43	57	0	0
,, ,, 130 –132.5	N E	20	35	75	50	40	15	5	75	75	50	35	10	5	66	55	60	65	15	
,, ,, 132.5–135	N E	10	10	40	40	80	50	0	40	60	90	80	30	10	50	80	70	90	30	0
,, ,, 135 –137.5	N E	19	0	0	32	58	52	21	5	10	53	63	53	47	21	26	48	47	26	16
,, ,, 137.5–140	N E	12	0	0	25	67	58	8	0	9	42	67	58	25	0	8	58	75	42	0
,, ,, 140 –142.5	N E	20	0	0	5	45	80	35	5	0	20	40	55	40	0	10	26	55	50	20
,, ,, 142.5–145	N E	14	0	7	4	14	50	22	0	0	21	29	29	36	14	14	36	36	29	14
37.5– 40 130 –132.5	N E	9	11	11	0	0	11	0	22	0	0	0	0	11	44	22	11	11	0	0
,, ,, 132.5–135	N E	12	42	67	50	42	42	8	50	92	58	33	50	33	33	33	33	25	33	33
,, ,, 135 –137.5	N E	22	14	41	27	39	45	9	32	41	50	32	22	36	23	36	69	68	50	14
,, ,, 137.5–140	N E	20	10	5	5	30	75	40	1	10	2	40	45	55	10	15	25	45	50	25
,, ,, 140 –142.5	N E	9	0	0	11	11	33	44	0	0	11	22	44	78	0	11	22	33	55	56
,, ,, 142 5–145	N E	17	6	0	6	0	41	70	6	0	6	0	29	59	0	12	29	29	41	47
40 – 42.5 130 –132.5	N E	6	0	60	33	0	17	0	16	17	0	0	0	0	17	17	50	17	0	33
,, ,, 132.5–135	N E	14	7	2	29	29	36	25	14	14	36	21	29	29	14	33	29	50	29	43
,, ,, 135 –137.5	N E	12	17	16	50	33	8	25	8	33	67	42	8	42	33	20	42	50	42	25
,, ,, 137.5–140	N E	8	0	13	13	25	38	62	0	0	13	0	0	25	12	0	0	25	50	50
,, ,, 140 –142.5	N E	12	0	8	8	8	17	50	0	0	27	8	8	8	0	17	25	50	42	67
,, ,, 142.5–145	N E	16	0	6	6	12	12	56	0	6	19	12	6	38	0	13	19	31	50	63

Position of Centre		N	P_1	P_2	P_3	P_4	P_5	P_6	M_1	M_2	M_3	M_4	M_5	M_6	J_1	J_2	J_3	J_4	J_5	J_6
40° – 42.5° 145 –147.5	N E	10	10	0	0	0	10	60	10	10	20	0	10	50	0	30	30	10	40	50
42.5 - 45 135 –137.5	N E	7	0	14	0	17	0	16	33	0	16	0	0	0	33	0	33	17	50	50
” ” 137.5-140	N E	12	0	0	0	8	0	82	0	0	0	0	8	33	0	0	0	17	25	67
” ” 140 –142.5	N E	15	7	7	7	7	7	40	0	7	7	0	7	47	0	0	7	20	0	73
” ” 142.5–145	N E	9	0	0	0	0	0	56	11	0	0	11	11	22	0	0	22	33	0	55
” ” 145 –147.5	N E	7	0	0	0	0	0	42	0	0	14	0	14	0	0	0	0	28	14	43
45 – 47.5 145 –147.5	N E	7	0	0	0	0	29	14	0	0	14	0	29	57	0	0	57	43	29	100
” ” 147.5-150	N E	7	0	0	0	0	0	42	0	0	14	0	14	100	0	14	43	28	29	86
47.5– 50 145 –147.5	N E	5	0	0	0	0	60	20	0	0	40	0	20	40	20	0	40	60	20	60
” ” 147.5-150	N E	10	0	0	0	0	20	0	0	0	0	10	50	70	10	10	30	40	60	40

From this table, we may easily trace the curves of equal expectation corresponding to each given position of the centre, or the locus of the positions of the centre bringing equal expectation for each given district. For the sake of simplicity call the former curves "the isohyets" for the given position of the centre, though here, instead of the amount of the precipitation, the expectation is meant; the latter sets of curves may be called "the centre loci" for the given district. To smooth down local irregularities, the average was taken of the expectations of four adjoining 2.5° meshes and the mean value was attributed to the centre of the four meshes. Those sets of four meshes of which any one had the number of occurrences of depression, i.e. N less than 5, were excluded. In this way, the uncertainty due to the defect of data in the marginal regions was avoided. From these averaged expectations we constructed the two sets of diagrams mentioned above.

Figs. 1 to 20 show the isohyets for different positions of the depression which is marked with $\ast$ in each diagram. Figs. 21 to 38 gives the centre loci for each district, the middle point of which is marked with ●.

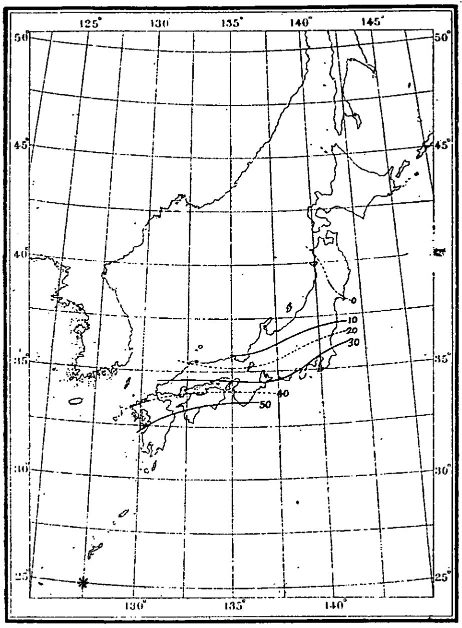

Fig. 1.

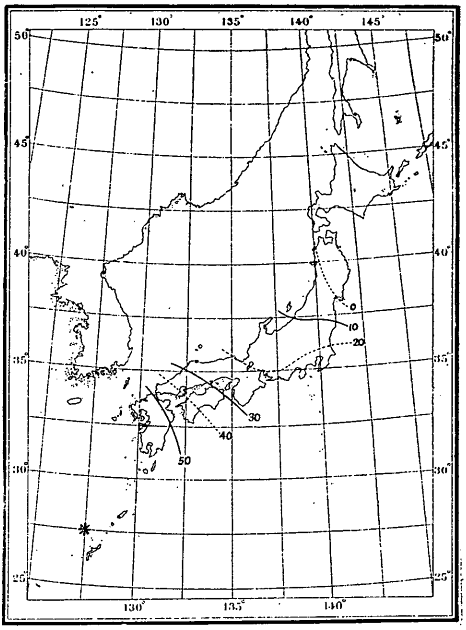

Fig. 2.

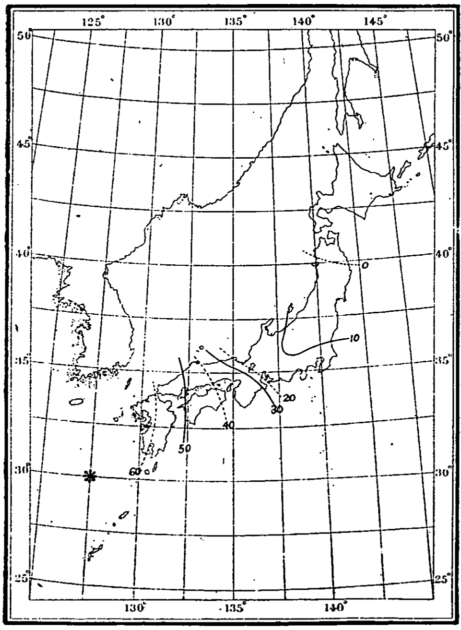

Fig. 3.

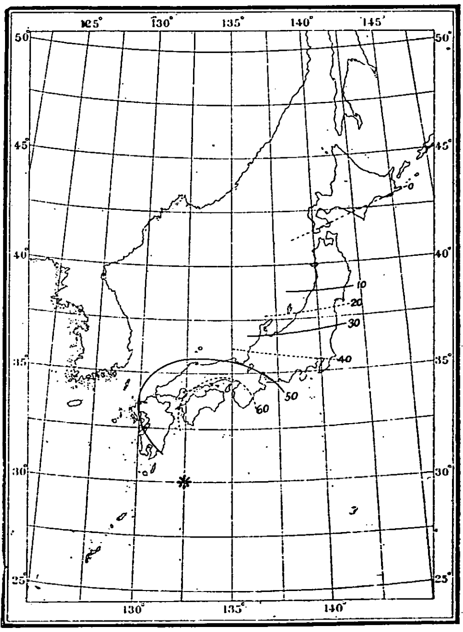

Fig. 4.

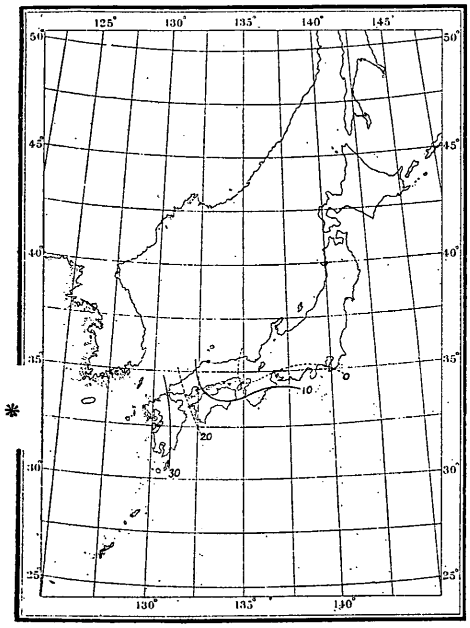

Fig. 5.

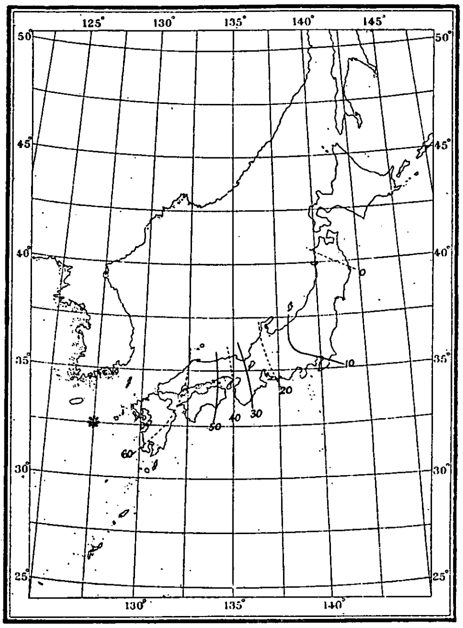

Fig. 6.

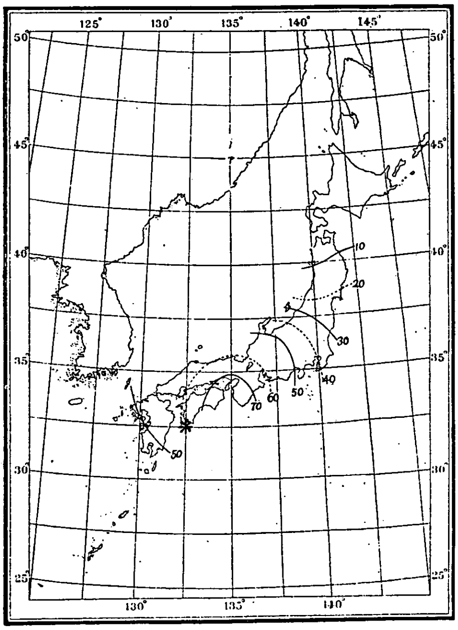

Fig. 7.

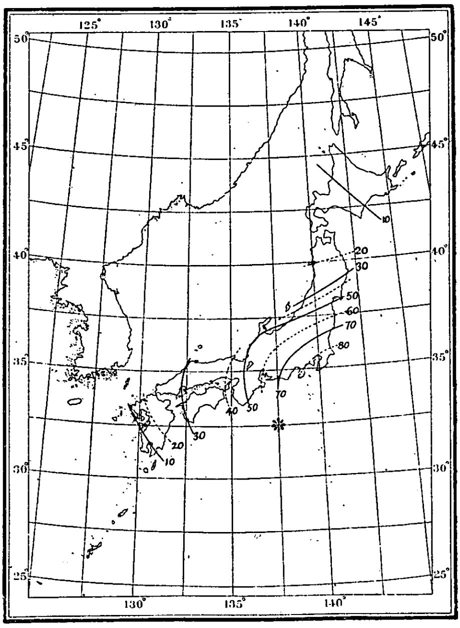

Fig 8.

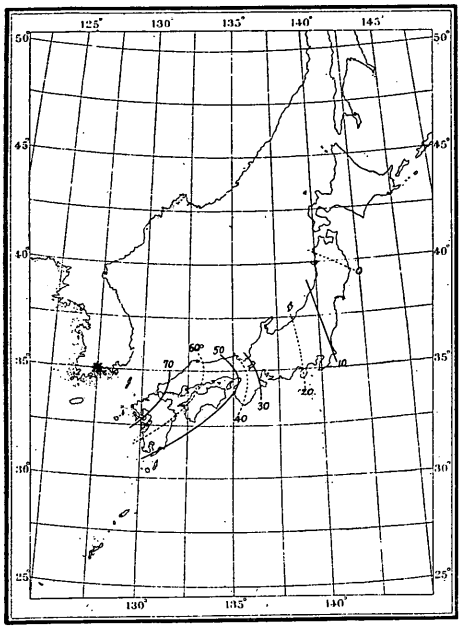

Fig. 9.

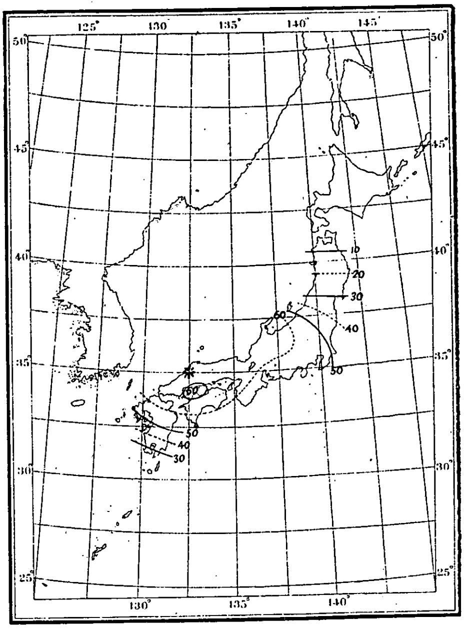

Fig. 10.

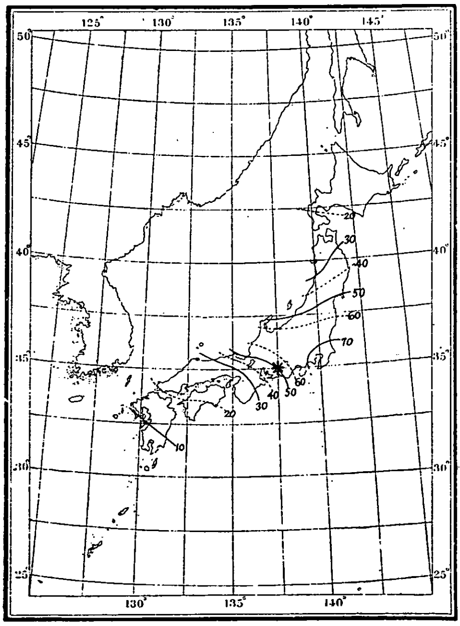

Fig. 11.

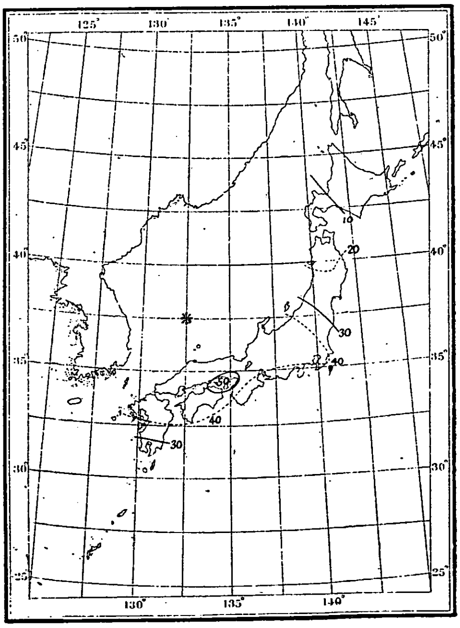

Fig. 12.

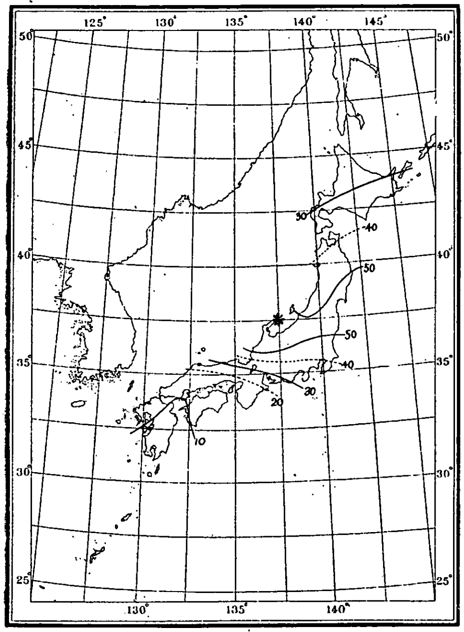

Fig. 13.

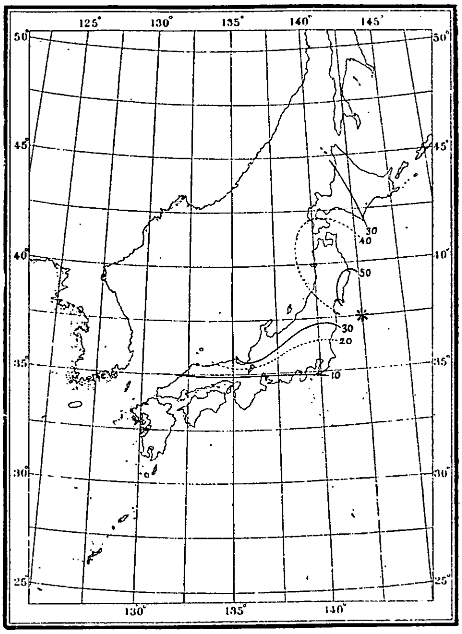

Fig. 14.

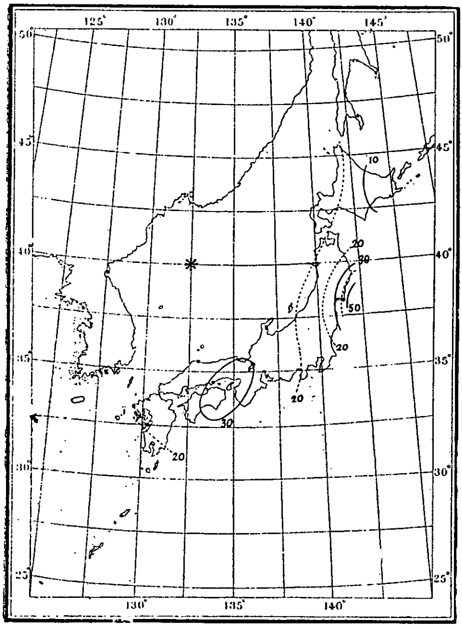

Fig. 15.

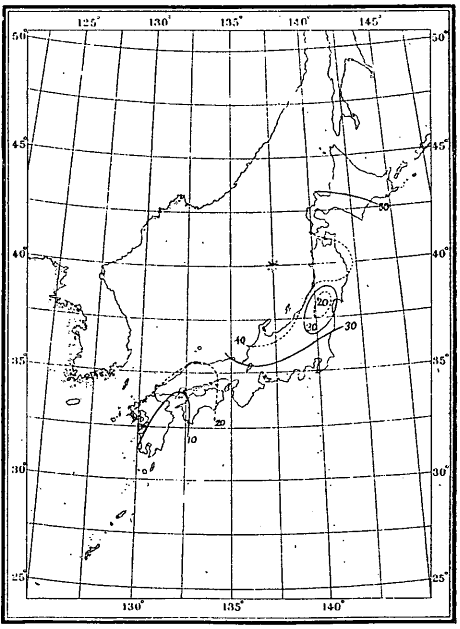

Fig. 16.

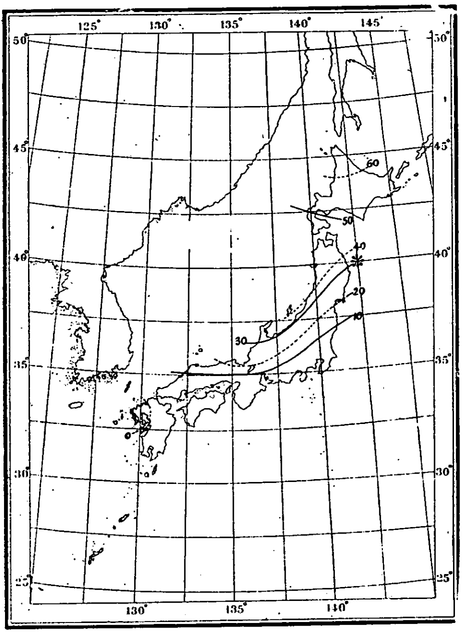

Fig. 17.

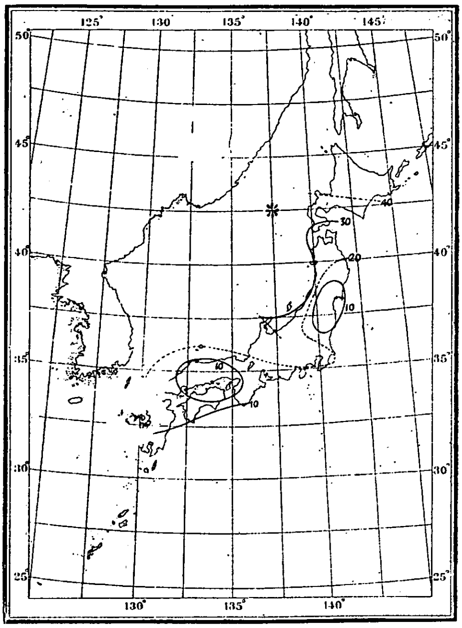

Fig. 18.

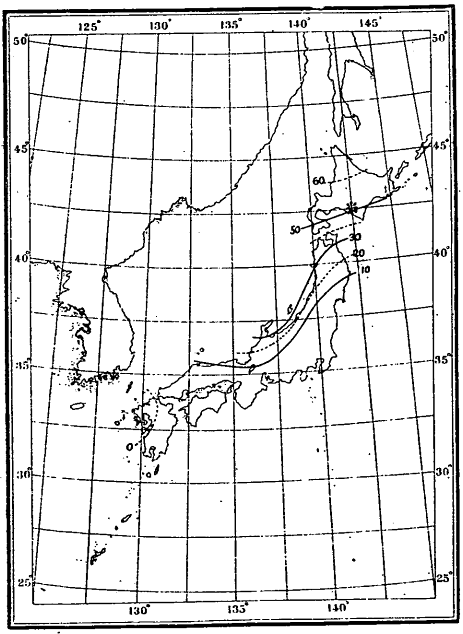

Fig. 19.

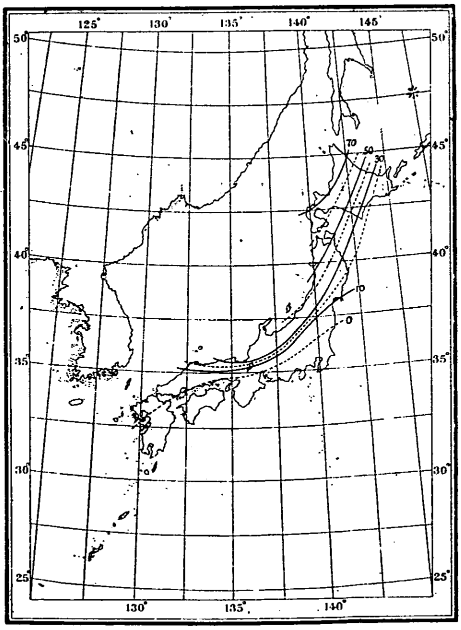

Fig. 20.

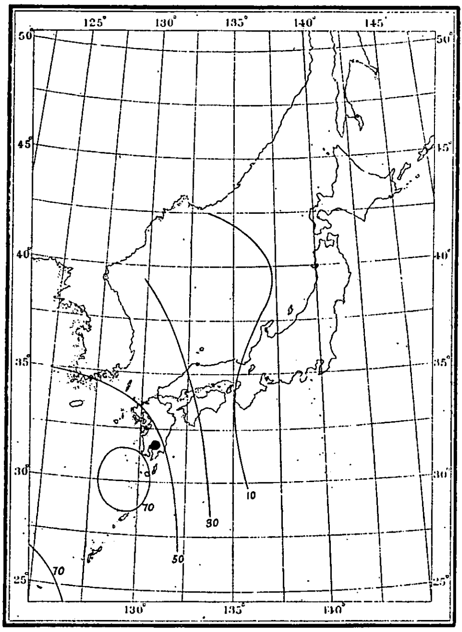

Fig. 21. P_1.

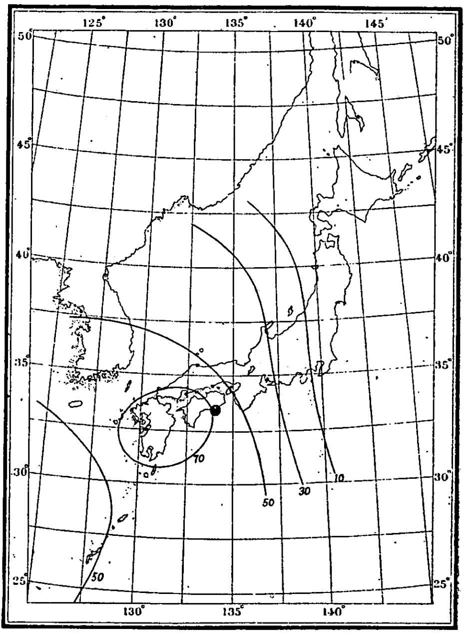

Fig. 22. P_2.

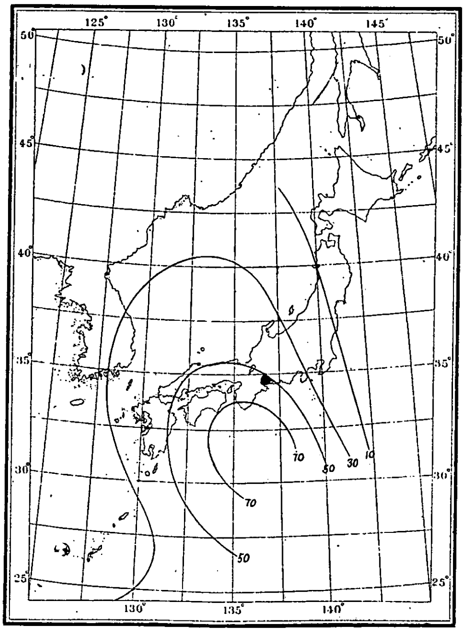

Fig. 23. P_3.

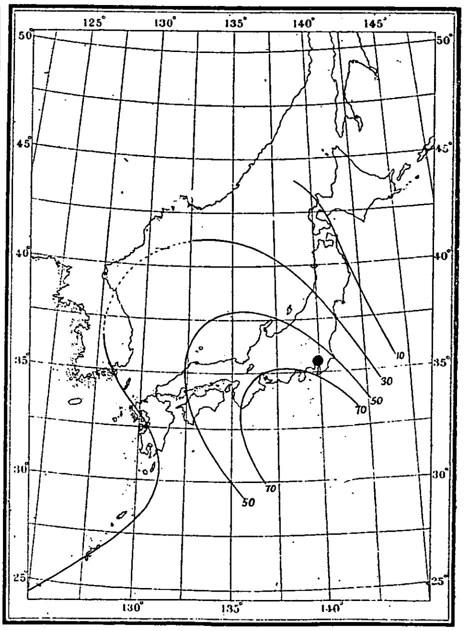

Fig. 24. P_4.

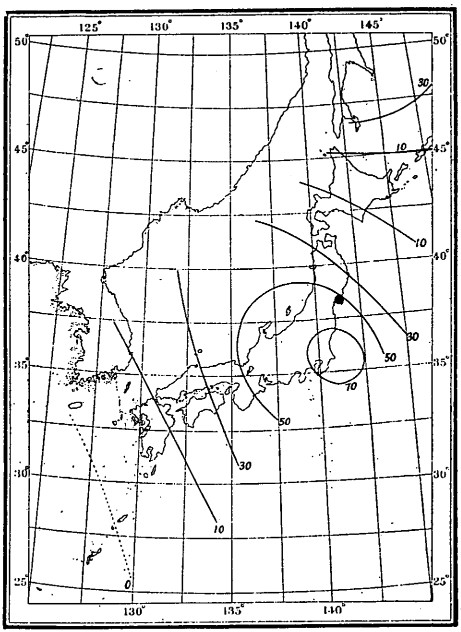

Fig. 25. P_5.

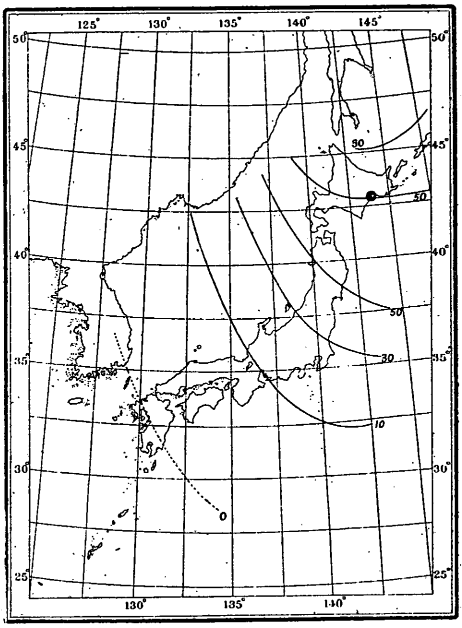

Fig. 26. P_6.

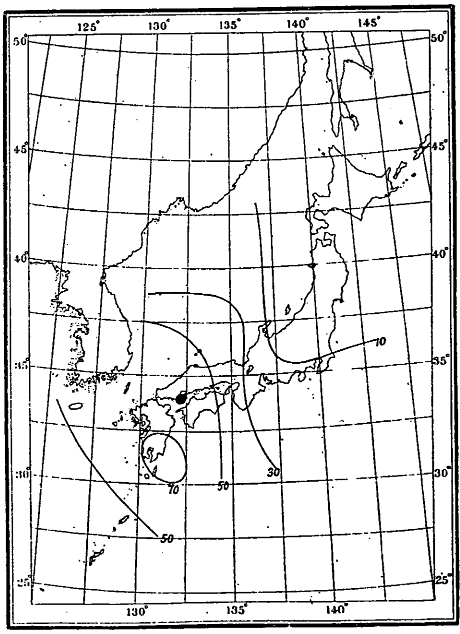

Fig. 27. M_1.

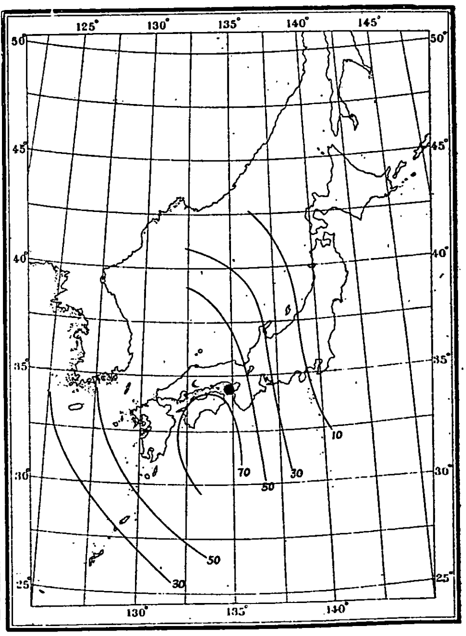

Fig. 28. M_2.

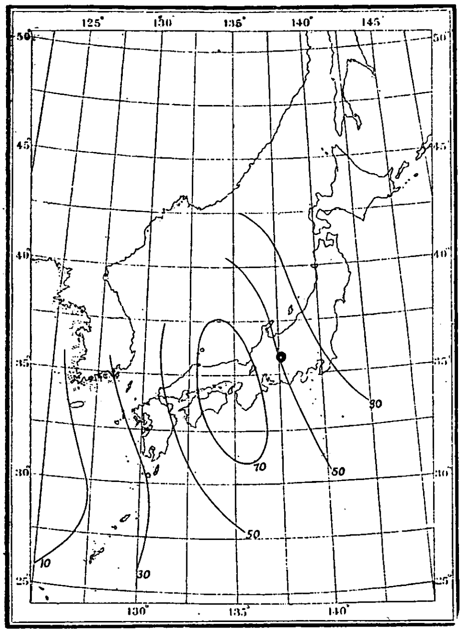

Fig. 29. M_3.

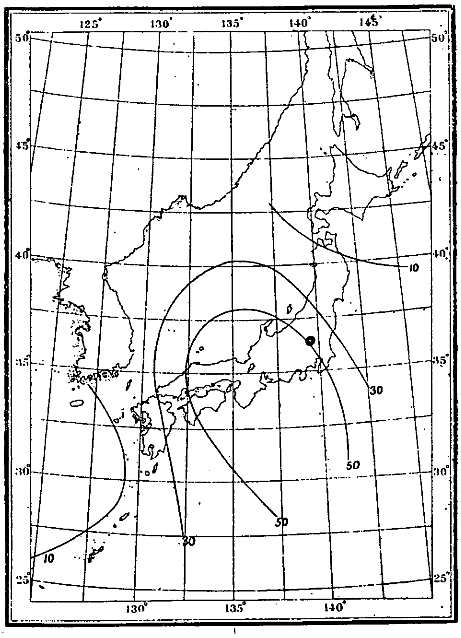

Fig. 30. M_4.

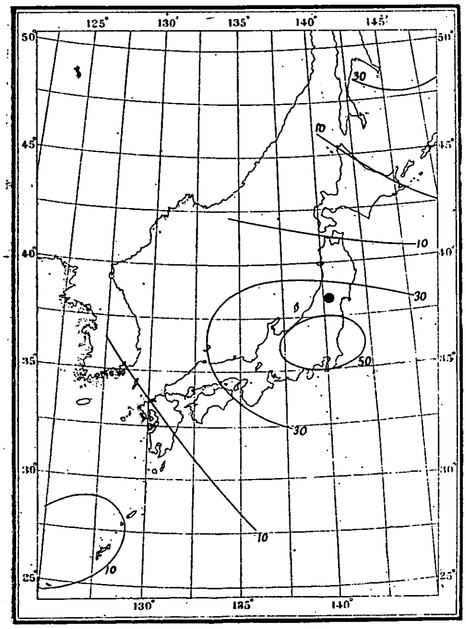

Fig. 31. M_5.

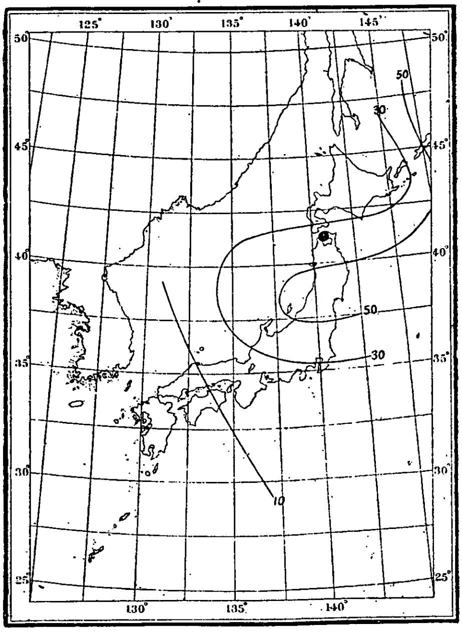

Fig. 32. M_6.

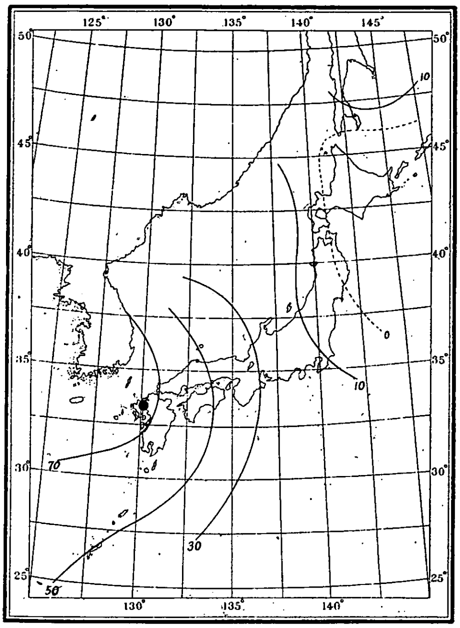

Fig. 33. J_1.

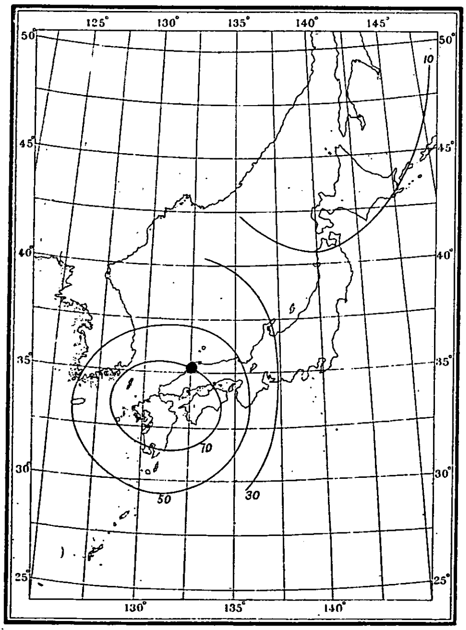

Fig. 34. J_2.

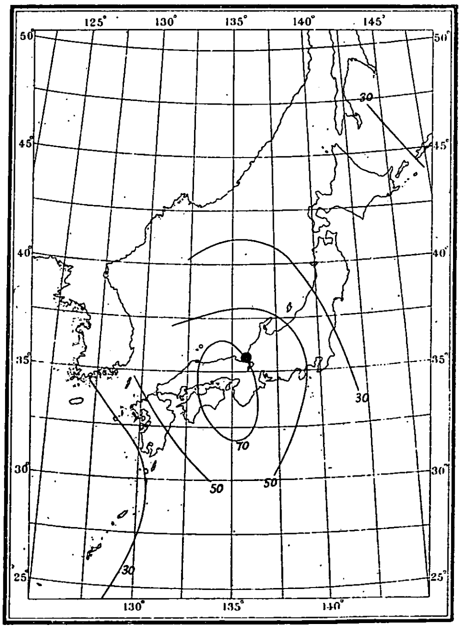

Fig. 35. J_3.

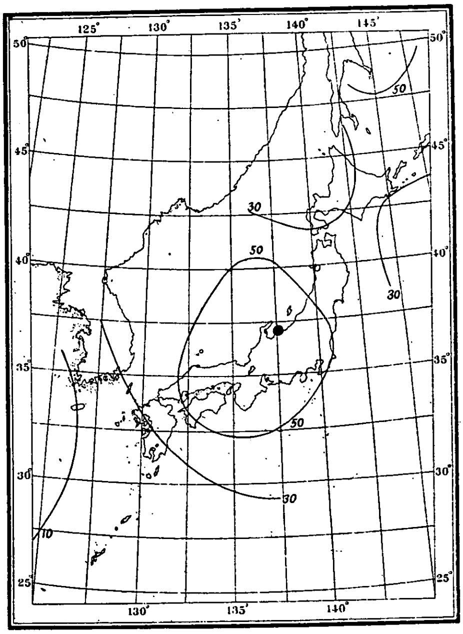

Fig. 36. J_4.

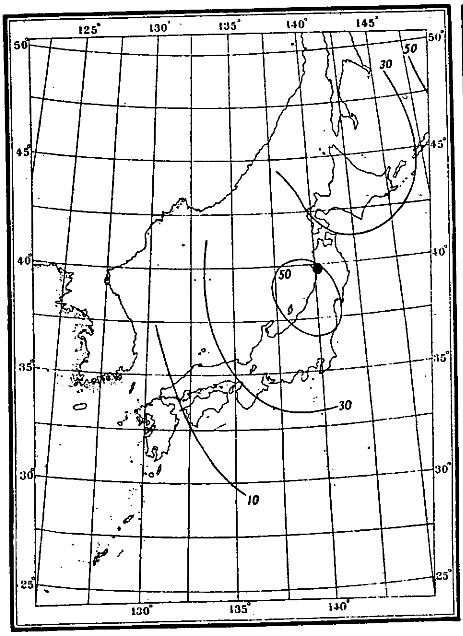

Fig. 37. J_5.

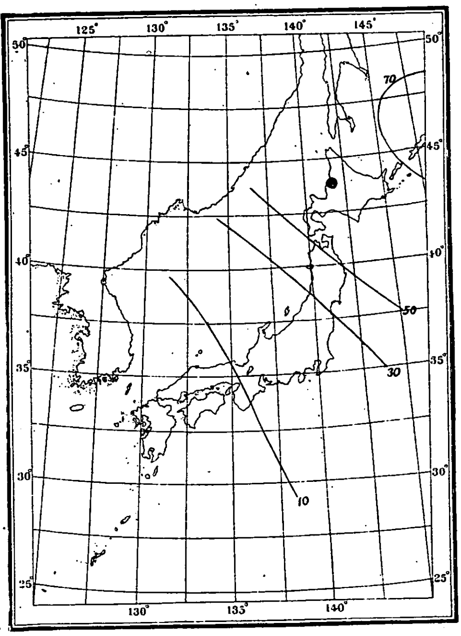

Fig. 38. J_6.

Discussion of the Results.

1.) Isohyets.

A passing glance at the isohyets will reveal the undeniable influence of the land and water. Referring to Figs. 1, 2, 5, 14, 17, 19 and 20, we see that in front of a distant cyclone, the Pacific coast has decidedly greater expectation than the Japan Sea coast, whereas on the rear side the reverse is the case. This fact has already been noticed and explained by one of us in the above cited paper. This relation is not so conspicuous as in the above example when the cyclone approaches the main island, though the same tendency is still suggested by the shape of some isohyets, as in Figs. 3, 4, 6, 7, 8, 11, 13, 16 and 18, especially in the regions remote from the centre of depression. In the immediate neighbourhood of the centre, the difference between the Pacific and the Japan Sea coast is not conspicuous, as may be seen from Figs. 3, 4, 6, 7 etc. It is quite evident that the above cited theory requires a modification in the inner region of a cyclone where the curvature of the isobars and the variation of the gradient could no more be neglected, and the ascending air current proper to this region is more conspicuous, so that the effect of the topography does not appear so pronounced as in the external region.

Comparing Figs. 5, 12, and 15, it may be seen that the district M_2 and probably also J_3 shows some local irregularities, which may probably be attributed to the peculiar configuration of land and water in this region. Next, referring to Figs. 15, 16 and 18, a tendency is suggested that when the centre lies in the Japan Sea, M districts often show smaller expectations than the neighbouring P or J districts. This peculiarity is most pronounced in the isohyets for the position of the centre, 132.5° E, 42.5° N which were omitted in the above diagrams, since the number of occurence N in two of the four meshes surrounding this point were less than 5. If we nevertheless calculate the corresponding expectations, we obtain

M_1	M_2	M_3	M_4	M_5	M_6	P_1	P_2	P_3	P_4	P_5	P_6	J_1	J_2	J_3	J_4	J_5	J_6
8	8	9	5	7	7	2	16	16	7	13	6	8	13	32	29	20	32

Thus the corresponding isohyets show a ''valley'' along the central axis of the main island. If this tendency is any thing real, the explanation must be sought in the draining influence of the Pacific mountain range lying on the wind side of this district, enhancing the ascending air current and condensing abundant moisture on the Pacific side. Moreover, it is interesting to notice that this particular position of the centre lies nearly at the centre of curvature of the circular axial line of Honsiu, and hence the geometrical relation of the different parts of the land with respect to the centre are similar to each other. This may at least explain why the isohyets in this case run nearly parallel to the land. On the contrary, when the centre of depression lies on the Pacific as in Fig. 8, not only the distance of, but the angle made by the coast line, with the radius vector drawn from the centre varies widely for different regions. This explains why the expectation in this case varies rapidly along the coast line. Nevertheless some peculiarities of the M districts similar to the above are suggested by the isohyets corresponding to some more remote positions of the centre than those shown in the above figures. These cases were, however, omitted on account of their small weight, and may better be postponed for a future research.

Again, comparing the Pacific and the Japan Sea coasts, for examples Figs. 7, 8 with 10, 13, or 4 with 16, the expectation seems to be generally greater for the Pacific districts than for the Japan Sea side, when the centre lies on the sea not far from the district in question. This may probably be attributed to the difference of temperature of the extended water bodies over which the wind comes.

Thus far we have considered only the average distribution of precipitation for different positions of the centre of depression. For the actual cases, the influences of an accidental nature, i.e. of the trivial local irregularities in topography, meteorogical conditions, etc., may give rise to various discrepancies compared with the average relations. Still it is not difficult to find a number of typical examples among the daily charts, which may well illustrate the above general inference. A few of these examples are shown in Figs 39 to 42.

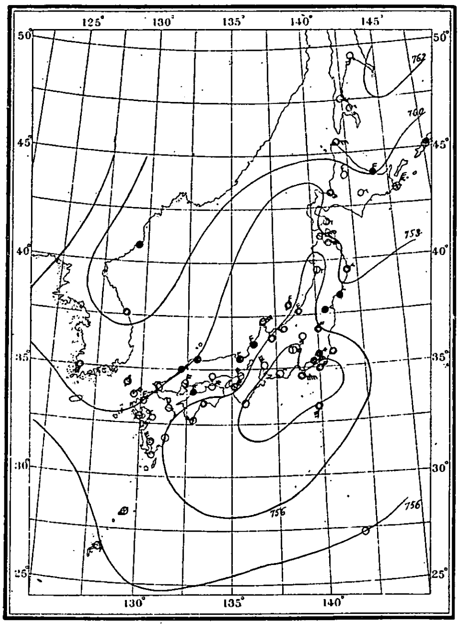

Fig. 39. 10ʰ p.m., July 30, 1913; compare with Figs. 11 and 14.

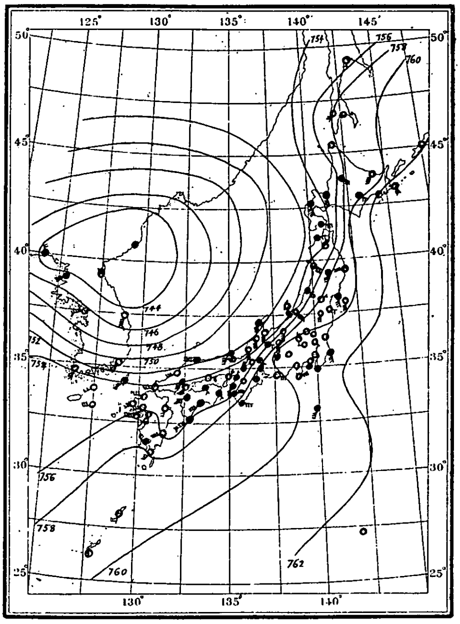

Fig. 40. 6ʰ a.m., April 23, 1913; compare with Fig. 15.

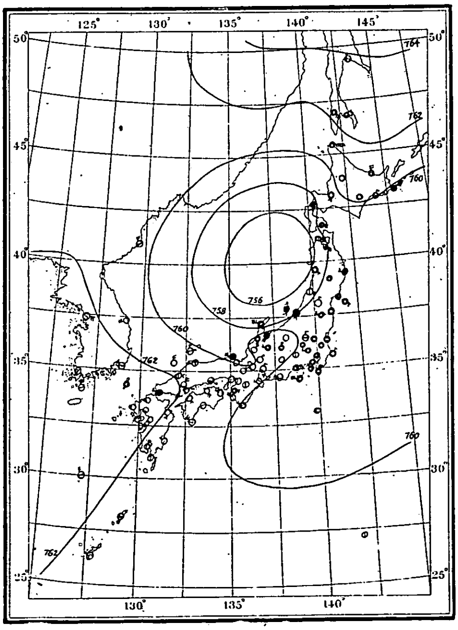

Fig. 41. 6ʰ a.m., October 19, 1913; compare with Figs. 13, 16 and 18.

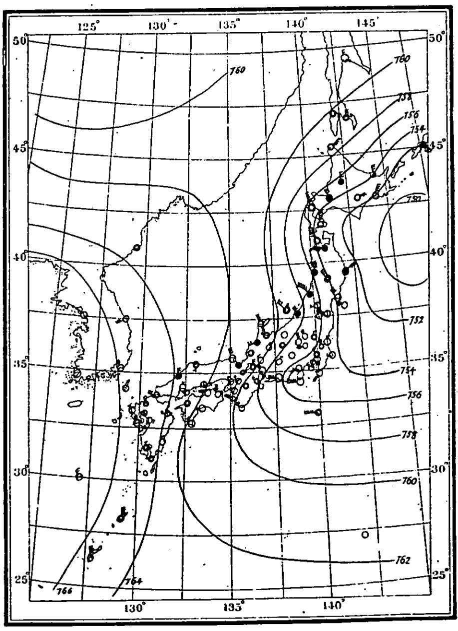

Fig. 42. 6ʰ a.m., Novemver 23, 1913; compare with Figs. 17 and 19.

2.) Centre Loci.

As already explained, Figs. 21 to 38 show for each of the 18 districts, the percentage expectation brought about by all possible different positions of the barometric depression. For example, in Fig. 21 the curve marked with 50 shows the trace of the positions of the centre which may bring precipitation to the district P_1 in 50 cases out of 100 on an average.

From these figures, it will be at once seen that the area with the greatest expectation lies mostly on W, SW or S side of the district in question. This implies that the expectation is generally greatest on E, NE or N side of a cyclone. On a closer examination, however, we may easily discern the characteristic difference between the Pacific and the Japan Sea coasts. For the P districts, the 50% curves generally pass along the immediate neighbourhoods of the middle point of the districts concerned and the areas with the greater expectations lie entirely on the W to S sides of the districts. For the J group, however, the districts in question lie decidedly apart from the 50% lines and nearer to the point with the maximum expectation ; moreover, the extent of the belt with 10 to 50% expectations in front of the district, is decidedly greater than that in the case of the P districts. Besides, J_2, J_4 and J_5 show a belt with the lesser expectation projecting far in advance of the district, while J_3, J_4, J_5 also suggest another maximum near Saghalien. For J_6 the district in question apparently lies on the rear side of the area with the maximum expectation. For the M districts, the relations are intermediate between P and J as may be expected.

One interesting relation revealed by this way of graphical representation may be worth a special description. Referring to Figs. 22 to 26, suppose a line drawn along the longer axis of the elongated area with expectations above 30 or 50 %, for each of P_1, P_2, P_3......P_6. The lines seem to turn round clockwise as we proceed successively from P_1 to P_6. The same tendency is more apparent for M_3 to M_6. The interpretation of this peculiar relation may probably be sought in the influence of the Japan Sea depressions.

We have already shown that when a centre lies far in the Japan Sea, the entire Pacific coast stands under nearly equal conditions, as far as the effect of the position of the coast line relative to the centre is concerned. Hence the influence of these depressions remains persistent when we proceed along the different districts. For the Pacific depressions, the case is quite different ; the isohyets cross the land more or less transversally, the expectation varying rapidly along the coast line. In other words, the part of the centre loci on the Pacific side moves *with* the centre, while on the Japan Sea side, it remains comparatively stationary.

General Theoretical Considerations.

Though we are afraid that we may be drawing our inference rather too far on the basis of too scanty materials, it will not be quite out of place to attempt here a discussion on the general theoretical aspect of the problem at hand.

Among the numerous factors determining the unsymmetrical distribution of precipitation due to a cyclone, we may conveniently distinguish the following three as the most essential :

(1) The first may be called "thermal and planetary" for the sake of simplicity. It consists in the difference of temperature with the latitude and may be considered always present regardless of the distribution of land and water. This influence would predominate if the earth were completely covered with ocean or land only, and would bring, according to the usual simple theory, more abundant rain on the eastern side of a depression.

(2) The second may conveniently be called "thermal and geographical" and consists in the difference of thermal conditions governed by the distribution of land and water, especially of continents and oceans. If this influence predominates, we may expect in the northern hemisphere the following : In summer when the land is generally warmer than the water, the area with the heaviest precipitation will lie in that direction which, viewed from the centre, has the land on the right side, provided of course that the land is sufficiently humid and the air kept nearly in saturation. But if the land be very arid, the reverse may occur, if

we can expect any precipitation at all. In winter, the relation will be different ; we may generally expect heavier rain or snow on that side of the depression which viewed from the centre has the ocean on the right side.

(3) While the above two factor are essentially thermal or thermodynamical, there remains the third one to be considered, which may conveniently be called "hydrodynamical and topographical." This consists in the effect of the forced ascending air current brought about by the discontinuity of the horizontal flow of air across the coast, due to the difference of "friction"* over land and water, or flat land and mountains. This effect has been discussed in the previously cited paper and may be summarized as follows : In the annexed figure, AB is the coast line bordering the land on its left side. PQ makes with AB a certain angle depending on the coefficient of friction on land and water. The ascending air current is induced when the gradient of the barometric pressure is directed toward the B side of PQ, while the descending current occurs when the gradient points to the A side. The absolute intensity of the current is maximum when the gradient is perpendicular to PQ, while it is zero when the gradient coincides with OP or OQ. This influence will appear most conspicuous where the land is in the shape of a narrow strip having a large extent of water bodies on both sides, provided the temperature and humidity on the two sides are not very different. Along the coast of a continent, however, the thermal and geographical influence mentioned under the previous paragraph will generally combine with the hydrodynamical influence, so that the relation may vary widely according to season or the physical conditions of the continent.

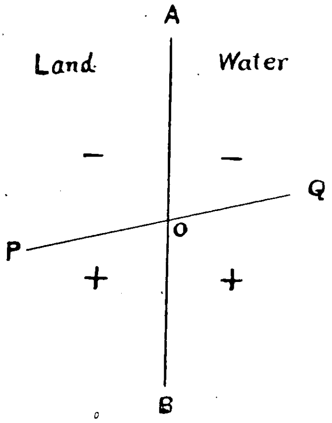

Fig. 43.

---

[*] In the sense of Guldberg and Mohn's theory.

In actual cases, these three influences are generally superposed, the resultant effect varying largely according to the degree of relative importance of each factor. For example, in the case of a deep depression of small extent, the first factor plays no greater part than slightly shifting the area with the heaviest precipitation toward E, while the second and the third factors may be important not only for determining the precipitation, but also the subsequent course of progression. It will be especially interesting to investigate the relation with respect to the cases of thunderstorms of the cyclonic type, i.e. those with circular depression in the centres.

The mathematical discussion of these different influences will not be easy, till we have at hand a more or less complete theory of cyclones in general. In the following, however, an attempt is made to illustrate the essential influences of the above mentioned factors for very simple ideal cases, and to found the starting point for analysing the actual complicated phenomena into their essential elements. It must be emphasized that the whole is nothing more than qualitative considerations expressed in mathematical forms.

(1) Planetary thermal influences: Referring to the annexed figure consider a centre of cyclone at 0 and draw two concentric isobars with the radii r and $r+dr$, in the inner region, i.e. the region where the ascending current proper to the cyclone is taking place. Suppose now all the isotherms are artificially maintained parallel to the x-axis. Assume the angle of deflection of the wind ψ, i.e. the angle between the barometric gradient and the wind, everywhere constant—an assumption apparently contradicting the idea of varying latitude, but since here we are only considering the effect of the thermal gradient, the small difference of ψ is evidently not essential. Then we may put

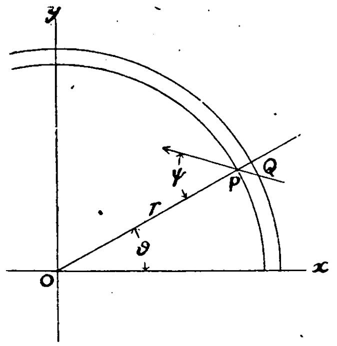

Fig. 44.

$$\mathrm{tg}\psi = \frac{2\omega \sin\varphi_m}{\kappa}$$

where φ_m is the mean latitude and $\varkappa$ the coefficient of friction in Guldberg and Mohn's sense. The flux across the circle with the radius r is $2\pi rv\cos\psi$ where v is the resultant velocity of wind at P, given by

$$v=\frac{G\cos\psi}{\varkappa}$$

in which G is the gradient accelaration :

$$G=K\frac{dB}{dr}$$

where B is the barometric pressure and K a constant.* The excess of the flux across the circle with the radius $r+dr$ is

$$2\pi\cos\psi\frac{d(rv)}{dr}dr=2\pi\frac{\cos^2\psi}{\varkappa}(G+r\frac{dG}{dr})dr.$$

Hence the total amount of the ascending current per unit length of the circular belt with the breadth dr is

$$\frac{\cos^2\psi}{r\varkappa}(G+r\frac{dG}{dr})dr.$$

If the air is kept artificially always in saturation corresponding to the momentary temperature as assigned by the given temperature distribution, the condensation of water vapor due to the ascending current will be proportional to the mean absolute humidity or nearly to the mean maximum vapor tension E between P and Q. The latter is well known as the function of temperature

$$E=f(T) \text{ say.}$$

Hence the condensation per unit horizontal area at P will be proportional to

$$R=\frac{f(T)}{\varkappa r}(G+r\frac{dG}{dr})\cos^2\psi. \tag{1}$$

If for example, $G=const.=G_o$, $R=\dfrac{f(T)\cos^2\psi G_o}{\varkappa r}$, (2)

or if $G=br$, $R=\dfrac{2f(T)b\cos^2\psi}{\varkappa}$, (3)

in which $f(T)$ may always be regarded as the function of the space coordinates of P, since T is given as such. This holds indeed

---

* Though of course, in actual cases, K involves the temperature of the air column, the above assumption may be allowed for the present purpose.

for any distribution of temperature, provided it is maintained stationary by any cause. In the present particular case, the curve of equal R will be parallel to the isotherms and be straight, if $G=br$, and R will increase toward the direction of the increasing T. When $G=const.$ and for example $T=T_0-Cy$, the curves will be given by $f(T_0-Cy)/\sqrt{x^2+y^2}=const.$ in Cartesian coordinates, which are generally concave toward the direction of increasing T. This will hold within the limit of the inner region and the effect will in any case tend to shift the centre of precipitation area toward the direction of the increasing temperature.

The quantity R is, however, not the only one in determining the precipitation. When the air proceeds from Q to P, the temperature must vary, due to the assumption that the isotherms are stationary. It will be easily seen from the figure that the temperature decrease is given by

$$dT=C\frac{\sin(\psi-\theta)}{\cos\psi}dr,$$

when $T=T_0-Cy$. Hence the unit volume of air, in proceeding unit distance along r, condenses out an amount of water given by

$$\frac{dE}{dT}\cdot\frac{dT}{dr}=\frac{df(T)}{dT}\cdot C\frac{\sin(\psi-\theta)}{\cos\psi}=R'. \tag{4}$$

This will be zero for $\theta=\psi$, positive for $\theta=\pi+\psi$ to $2\pi+\psi$, and negative (i.e. evaporation instead of condensation) for $\theta=\psi$ to $\pi+\psi$.

The total precipitation will then be proportional to $R+R'$ in which the effect of R' is in any case to shift the centre of the heaviest precipitation toward the direction $\theta=\frac{3\pi}{2}+\psi$. In the above, it has been assumed that R at any place is merely due to the condensation caused by the vertical current at that very spot. In the actual case, however, the ascending air is transported leewards by the horizontal current to an extent depending on the ratio of the horizontal velocity to the vertical, and also to the height of the cloud layer. This effect will result in deforming and twisting the isohyets as a whole in counterclockwise sense.

Moreover, even if the isotherms were originally parallel to the latitude, they will be distorted counterclockwise as is well known, since the artificial assumption does not hold that the earth's surface as a sensitive heat reservoir keeps the air always in the temperature prescribed for the latitude. These effects taken altogether, will tend to drive the area of the maximum precipitation toward the eastern side of the depression.

(2) Geographical thermal influences. When the coast line is straight and the air is everywhere saturated, the reasonings of the preceding paragraph exactly apply to this case, only that the temperature gradient is here everywhere small, except in vicinity of the coast line. The part of the precipitation due to the term R of the preceding paragraph will be abundant on the warmer half-plane. The influence of the term R' will be only sensible in a narrow zone along the coast line if the variation of temperature across the coast be abrupt or discontinuous. If in the land area the air is not saturated, the case may differ, according as the absolute humidity is greater or less than on the sea. In the special case when in summer the absolute humidity on a very arid land is small compared with that on the colder sea, the result will be reverse to that in the above case, so far as we take no account of the horizontal transport. The ascending current must, however, in either case be carried leeward as already remarked. Hence we can expect precipitation on the coast of a dry land where the wind comes from the sea. In the normal case, when the air is everywhere saturated, the isohyets will simply be twisted clockwise, so as to increase the precipitation on the coast lying on that side of the centre, which viewed from the centre have the warmer half plane on the right side.

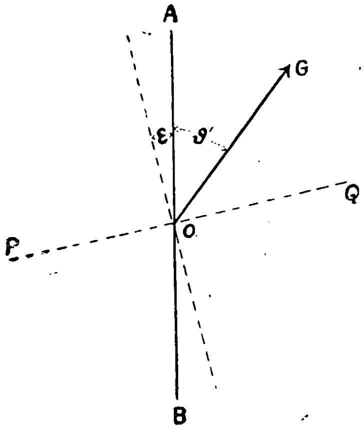

Fig. 45.

(3) Hydrodynamical topographical influence. Suppose AB is a portion of the coast line bordering the sea on its right

side. OG shows the direction of the barometric gradient which makes an angle θ' with OA. Here the essential difference of land and sea is assumed to consist in the difference of the coefficients of friction, $\varkappa$ and $\varkappa'$ respectively; the other thermal behaviours are supposed to be equal on both sides. It has been shown in the above cited paper that the intensity of the ascending current due to the discontinuity of the horizontal flux across AB is given by

$$\delta = D\cos(\theta'+\varepsilon)$$

where

$$D\cos\varepsilon = \tfrac{1}{2}(\cos 2\psi - \cos 2\psi'), \qquad \mathrm{tg}\psi = \frac{c}{\varkappa},$$

$$D\sin\varepsilon = \tfrac{1}{2}(\sin 2\psi - \sin 2\psi'), \qquad \mathrm{tg}\psi' = \frac{c}{\varkappa'}.$$

If $\psi = 61^\circ$, $\psi' = 42^\circ$, then $D = -0.3255$, $\varepsilon \doteqdot 13^\circ$.

Since D is usually negative, the ascending current at O will be maximum when $\theta' = \pi - \varepsilon$, and zero when $\theta' = -\left(\frac{\pi}{2}+\varepsilon\right)$ or $\frac{\pi}{2}-\varepsilon$. For $\theta' = -\left(\frac{\pi}{2}+\varepsilon\right)$ to $\frac{\pi}{2}-\varepsilon$, the vertical current will be directed downwards; hence the expectation of precipitation at O will be none for these directions if there is no general ascending current proper to the depression. In the case when O lies within the inner region of a cyclone, the ascending current at this point proper to the cyclone will be enhanced when the centre lies on the B side of PQ, but weakened when it lies on the epposite side. If there exists no such hydrodynamical influence, the trace of the cyclonic centre bringing equal expectation to O, will evidently be a circle with O as the centre. In the special case, when the gradient is proportional to the distance from the centre, or $G = br$, R will be independent of r, as may be seen from (3) since here the temperature is assumed constant. In general cases, however $R+R'$ will be a function of r and θ' as may be seen from (2). Denote this by

$$R+R' = F(r\theta').$$

Taking the hydrodynamical influence in account, the centre loci will be given by

$$F(r\theta') + D\cos(\theta'+\varepsilon) = const.$$

where r and θ' are the polar coordinates, with O as the origin and OA as the prime vector. It will be seen, that whatever may be the form of $F(r\theta')$, the effect of the second term will be to shift the centre of area of the loci loci toward the direction $d=\pi-\varepsilon$.

From the above, it will be seen that the first and the second factors are essentially not very different, and there would have been no special need at all to distinguish them, if we are everywhere concerned with humid land only. In the latter case, the essential factor is only the distribution of the isotherms, and the results of the above considerations in the paragraphs under (1) and (2), may be summarized as follows : The maximum precipitation will be expected on the right front quadrant when we look out from the centre of depression toward a direction having the warmer half plane on the right side, provided the isotherms are maintained nearly stationary regardless of the cyclone. The latter condition will be nearly fulfilled when the general temperature distribution is determined by an extensive "centre of action."

When we consider the three factors as separate, it will be seen that the second and third generally conspire in winter, but tend to cancel each other in summer, provided the land and water are of sufficient extent. For a narrow strip of land such as Japan, the second factor will play no important part when a cyclone of considerable dimensions is concerned, since in such a case the assumption does not apply that the land behaves as a reservoir of heat determining the stationary isotherms, regardless of the disturbance due to the cyclone itself. Meanwhile the third influence remains, since it will be independent of the latter disturbance.

Next the first and the third influences conspire when a coast line running more or less in west-easterly direction, face to the water on its southern side, but tend to cancel each other when the water is on the northern side. The resultant effect is well illustrated by comparing the centre loci diagrams for P and J districts. That the first influence predominates in these cases, is shown by the fact that the district in question lies generally on the eastern side of the point of maximum expectation, though yet the eccentricity is more decided in the case of the Pacific coast than in the

Japan Sea districts. The latter fact still shows the unerring effect of the third factor.

Hann remarks that on the northern side of the Alps, the rain fall is most abundant on the rear side of a barometric minimum. This fact may probably be explained by the predominating influence of the hydrodynamical factor, since the effect of a great mountain range is equivalent to the increase of the coefficient of friction. That northern Germany, including Swinemünde and Breslau, has maximum rain fall on the rear side of a depression, may be understood by the combined effect of the second and the third factors. The case of Great Britain investigated by Mill, seems at first sight irreconcilable with the above considerations, since the heaviest rainfall area occurs on the left side of the track of the centre, contradicting in most cases the influence of the third factor. But it must be remembered that Mill's results refer to the "smear" in which the rainfall on the front and rear sides of the centre are supesposed. He states, indeed, that the heaviest rainfall occurs in advance of the centre. The influence of the third factor combined with that of the first one may in some cases shift the centre of the smear to the left side of the track ; the front rain falling on the eastern side of land or mountain is abundant on the northern side of the track, due to the third influence, while the rear rain is abundant on the southern side of the track, on the western side of the land, or any orographic irregularity ; hence if due to the first factor, the rear rain is less abundant than the front rain, the centre of the smear will lie on the northern side of the track. This seems to explain most cases given by Mill where the depressions proceed toward E. In order to explain different cases in which the relation is apparently not so simple as considered above, exact knowledge is of course necessary of the thermal and topographical conditions of the district concerned for each particular case.

Finally, it must be remarked, to avoid misunderstanding, that the present discussions involve no essential novelty as a theory of cyclonic rainfall, except emphasizing the importance of the hydrodynamical influence due to the difference of the coefficient of friction. The above may only be regarded as suggesting a way toward the better understanding of the complicated rain problem. The discussions refer to different ideal cases, underlying several artificial simplifying conditions. Above all, the assumption is made that the thermal conditions are prescribed independent of the cyclone, and the secondary disturbances both thermal and topographical due to the cyclone itself, are entirely put out of account. The latter disturbances may in some cases modify the resultant effect of the other primary factors in no small degree. Still, we are inclined to believe that the above way of analysing the complicated influences in these principal factors may in many cases facilitate a better understanding of the phenomena of cyclonic rainfall, and if properly understood and applied may be utilized for the purpose of weather prediction.

In conclusion, we wish to express our best thanks to Prof. T. Okada of the Central Meteorological Observatory for many valuable informations.

Published January 27th, 1916.