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# On the Heavy Rainfall in the Kinki District (Western Japan)

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**Abstract**

In this district there is one of the rainiest areas in the middle latitudes. In order to clarify the mechanism of heavy rainfall, we chose this district as a model region. We investigate heavy rainfall only in the warm season when much data are available. First, comparing the distributions of total precipitation, number of rainy days, 24-hour precipitation and hourly precipitation in the warm season with each other, we investigate the features of rainfall climatologically. Then analyzing 4-day mean 500 mb height patterns in the cases of heavy rainfalls, it is shown that there is an intimate relation between the long wave pattern in the Far East and the heavy rainfall over this district. Finally, comparing some examples of heavy rainfalls over the central part of the Kinki district accompanied by the strong south-westerly humid current, the factors generating the heavy rainfall are discussed.

## 1. Introduction

Japan is close to the east coast of the Asiatic Continent and Western Japan especially is located in the humid subtropical climate region. The Kinki district in the eastern part of Western Japan is one of the rainiest districts in the middle latitudes. In this district mean annual precipitations are about 1200～4000 mm or more. The distance between the places where the precipitations are 1200 mm and 4000 mm is only 100 km. Heavy rainfalls of which 24-hour precipitation is more than 100 mm frequently occur. The Kinki district is therefore a very interesting model region for the study on rainfall. In this region thanks to the recent development of water resources the network of rainfall observation has become dense enough for detailed analysis. Here, we discuss first about some climatological questions concerning rainfall frequency and distribution in the warm season by the aid of such detailed data. Secondly we seek for the remote causes of the heavy rainfall by a large scale analysis of upper atmospheric weather charts in the Far East. Finally we investigate the remarkably heavy rain bands extending from the vicinity of Osaka Bay towards Lake Biwa when south-westerly currents prevail in the lower troposphere.

## 2. Climatological Description

Fig. 1 is a topographical map of the Kinki district showing the distributions of important rivers and mountains (areas of 800 m height or more above the sea level are shaded). The Kii Mountains in the southern Kinki district are about 1000～2000 m high and these mountains extend north-eastward to the Suzuka Mountains and the Ibuki Mountains. On the other hand, the Chugoku Mountains of the 1000 m level extend from the Chugoku district to the western

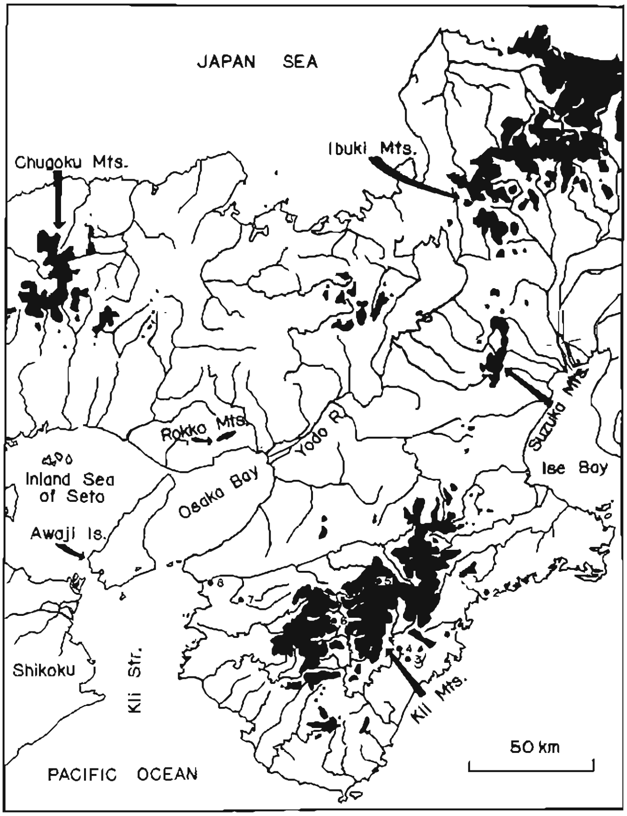


Fig. 1. Mountains (the height of the shaded area is 800 m or more above the sea-level) and rivers in the Kinki District.

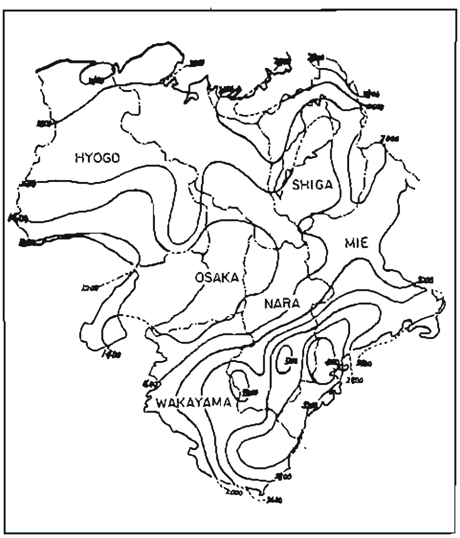


Fig. 2. Normals of annual precipitation (in mm, 1921~1950) after K. Wadati.

Kinki district. In Shikoku also there are mountains of the 2000 m level. The less rainy plain surrounded by these mountains extends from the Seto Inland Sea to the central part of Kinki.

In Fig. 2 showing the distribution of the mean annual precipitation in the Kinki district quoted from "Climate of Japan"[1] there are two rainy areas. One lies along the Pacific Coast and the other lies along the Japan Sea coast. Rainfall in the two rainy areas are mainly caused by the south-westerly monsoon in summer and the north-westerly monsoon in winter respectively.

As in recent years the number of rainfall observation stations has increased very much, investigation of the distributions of hourly precipitation and 24-hour precipitation has become possible. So the duration of observation is rather short for making a statistical study. Since many of the stations were set up for the prevention of flood disasters, observations are carried out only in the warm season, from June to October.

Fig. 3 shows the distribution of the mean precipitation in the warm seasons for 1965 and 1966. In Fig. 3 the maximum of the precipitation is not in the area facing the Japan Sea as shown in Fig. 2, but the rainy area extends from the central part of Hyogo Prefecture to the central part of Kyoto Prefecture in the warm season. The maximum precipitation appears near the Pacific Coast

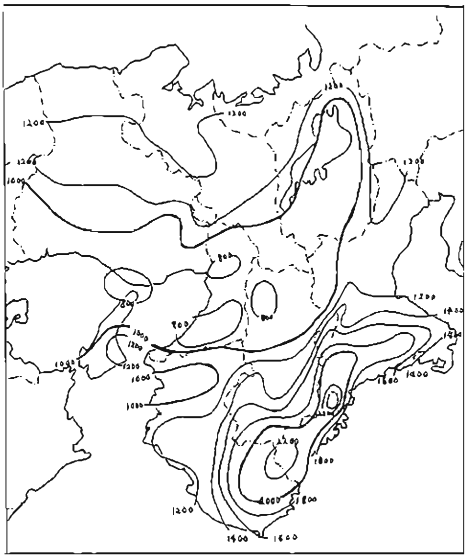

Fig. 3. Total precipitation in the warm season (in mm, Jun.～Oct.). Mean values of 1965 and 1966 are used.

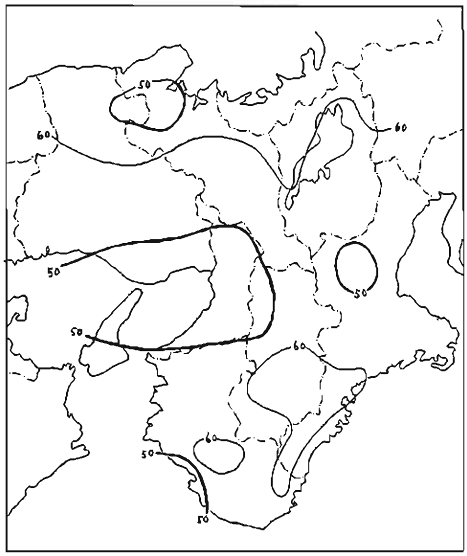

Fig. 4. Total number of rainy days (daily precipitations are above 1 mm) in warm season.

TABLE 1.

| Station | Height above the M.S.L. (m) | Total rainfall in the warm season (mm) |
|---|---|---|
| 1. Owase | 14 | 2453 |
| 2. Nagashima | 3 | 1769 |
| 3. Isato | 200 | 2030 |
| 4. Terakaito | 360 | 1870 |
| 5. Sanjōgadake | 1700 | 1266 |
| 6. Kojindake | 1250 | 1436 |
| 7. Higashinogami | 65 | 986 |
| 8. Wakayama | 14 | 1047 |

and is about four times the minimum along the Seto Inland Sea.

The precipitation over the lowland in the central part of the Kinki district is small. Corresponding the precipitations at various stations to their height,

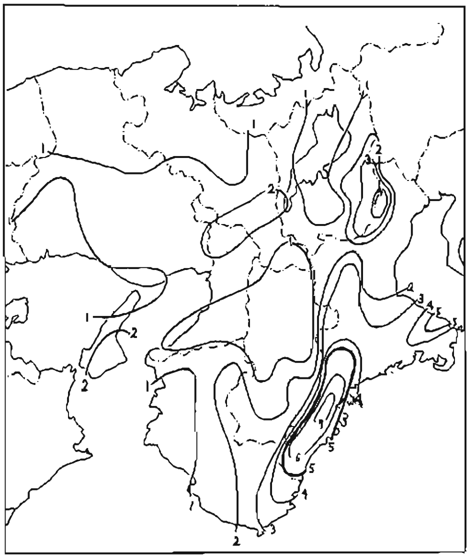

Fig. 5. Total number of days when daily precipitations are 101 mm or more in warm season.

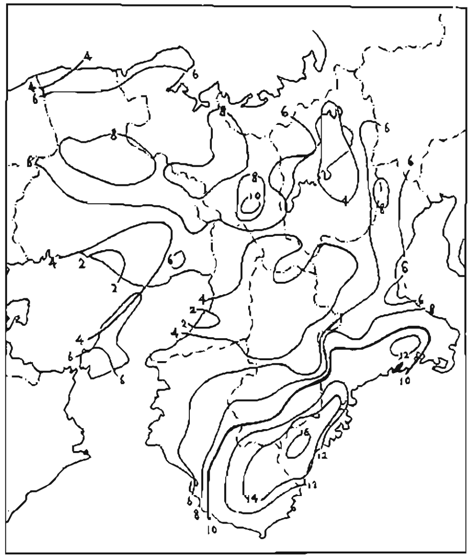

Fig. 6. Same as Fig. 5 but for the daily precipitation 51 mm or more.

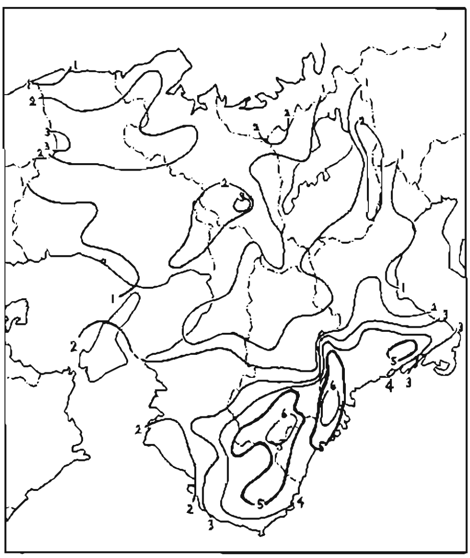

Fig. 7. Total number of hours when hourly precipitation are 31 mm or more in warm season.

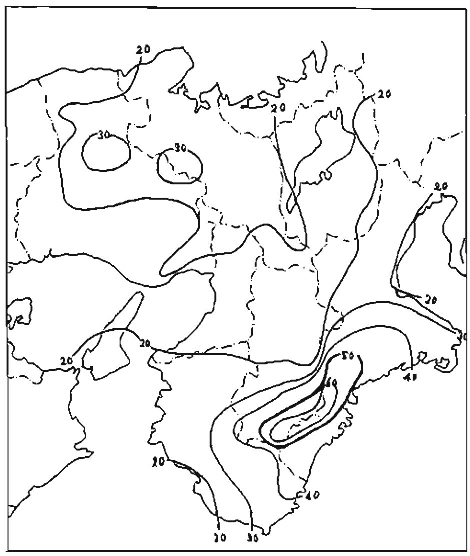

Fig. 8. Same as Fig. 7 but for the hourly precipitation 10 mm, or more.

the precipitation is not proportional to the height over the mountainous region in the southern Kinki district. As exampels the height and the precipitation in warm season at the eight stations along the east-west line across the Kii Mountains are listed in Table 1. The positions of the stations are shown in Fig. 1 in number. This table suggests that the causes of rainfall in this area are not restricted to simple orographic upgliding.

Fig. 4 shows the distribution of number of rainy days (when 24-hour precipitation is 1 mm or more) in the same period. The distribution of rainy days is considerably uniform all over the Kinki district in comparing with that of total precipitation in Fig. 3. This means that each fall of rain is heavy in the area where the total precipitation is large.

Fig. 5 and Fig. 6 show the distributions of number of days when 24-hour precipitation is 101 mm or more and 51 mm or more respectively in the same period. Comparing these with Fig. 4, it becomes to be clear that in the southern part of Mie Prefecture 24-hour precipitation is 101 mm or more for about 10 percent of rainy days and that is 51 mm or more for about 25 percent. On the other hand, 24-hour precipitation scarcely exceeds 51 mm along the Seto Inland Sea.

Fig. 7 and Fig. 8 show the distributions of number of hours when hourly precipitation is 31 mm or more and 10 mm or more in the same period respectively. These figures show the somewhat different features in the distribution from those of 24-hour precipitation and total precipitation. That is, in Fig. 7 the two heavy rainfall areas are strikingly seen with high concentration of precipitation, one extends north-eastward from Mie Prefecture to the eastern part of Shiga Prefecture and the other from Awaji Island to the central part of Kyoto Prefecture. Fig. 7 and Fig. 8 show that the number of hours when hourly precipitation is 10~30 mm is not so different over the whole area, though there is much difference in the total precipitations as shown in Fig. 3. As shown in the statistical report on thunderstorms issued from Osaka District Meteorological Observatory[2], thunderstorms are not so frequent in the rainy southern Kinki district, but are frequent in the central part of the Kinki district. This fact may explain the features of the distribution shown in Fig. 8.

## 3. The relation of heavy rainfall in the Kinki district to the large scale flow pattern in the upper troposphere.

As mentioned above, over the mountainous region in the southern Kinki district heavy rainfalls frequently occur in the case of typhoons, while over the lowland in the central Kinki district those often occur in the period from the last of Baiu to midsummer, sometimes in spring and autumn. In such cases some common features of long wave pattern appear in the upper troposphere: the polar jet stream comes down southward into the vicinity of Japan and is intensified considerably, in other words cold air from the north comes down southward, and blocking patterns frequently occur. Nine examples will be shown in the case in which 24-hour precipitations were more than 100 mm over the lowland in the central Kinki district, and the general weather condition and corresponding 4-day mean 500 mb height pattern will be discussed.

Example 1. For 12~14 August 1958, 48-hour precipitation is 200~500 mm and

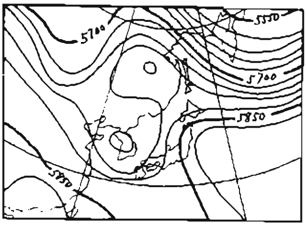


Fig. 9. 4-day mean 500 mb height pattern for 11～14 August 1958.

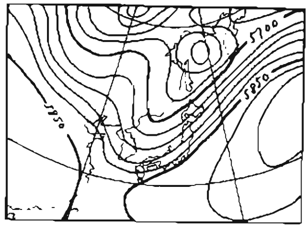


Fig. 10. Same as Fig. 9 but for 12～15 July 1959.

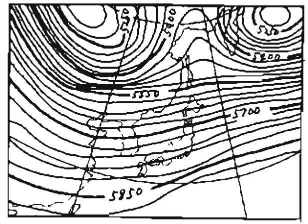


Fig. 11. Same as Fig. 9 but for 1～4 October 1959.

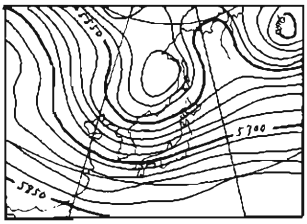


Fig. 12. Same as Fig. 9 but for 17～20 May 1960.

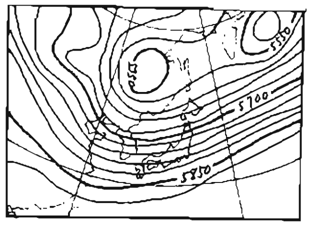


Fig. 13. Same as Fig. 9 but for 20～23 June 1960.

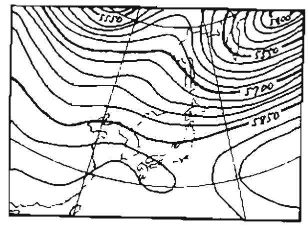


Fig. 14. Same as Fig. 9 but for 12～15 August 1960.

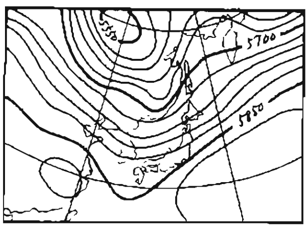


Fig. 15. Same as Fig. 9 but for 25～28 June 1961.

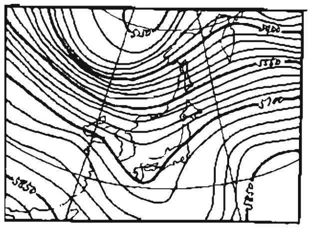


Fig. 16. Same as Fig. 9 but for 26～29 October 1961.

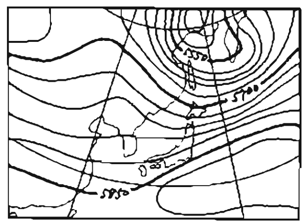


Fig. 17. Same as Fig. 9 but for 7～10 July 1967.

a frontal line accompanied with a cyclone goes up northward to the Japan Sea from the Pacific coast of Honshu. Fig. 9 shows the 4-day mean 500 mb height pattern for 11～14 August. This is a typical blocking pattern.

Example 2. On 14 July 1959, a cyclone moves eastward from Central China along the north coast of Honshu, while typhoon 5905 moves northward along the east coast of China, and heavy rainfall occurs in the central and southern Kinki district and in the eastern part of Shikoku. Fig. 10 shows the 4-day mean 500 mb height pattern for 12～15 July, which indicates a remarkably developed trough extening from the sea of Okhotsk through the Japan Sea to the East China Sea.

Example 3. For 2～3 October 1959, a well developed cyclone moves eastward over the Japan Sea and heavy rainfall with thunderstorms occurs over a rather small area in the vicinity of Osaka at the passage of a cold front. The 4-day mean 500 mb height pattern for 1～4 October shown in Fig. 11 is rather zonal in the vicinity of Japan. But cold air coming from the pole intensifies the westerly current in the vicinity of Japan and the weak trough is over the

East China Sea. Such a condition is favourable for the development of a cyclone over the Japan Sea.

Example 4. On 19 May 1960, after a cyclone moves eastward over Western Japan, the second cyclone accompanied with the cold front moves eastward along the south coast of Japan. Heavy rain concentrates mainly in the vicinity of Osaka and Kobe. Fig. 12 shows the 4-day mean 500 mb height pattern for 17~20 May, which shows the deep trough extending from eastern Siberia to the East China Sea and the developed ridge from east of Honshu to the Sea of Okhotsk.

Example 5. For 21~22 June 1960, the front staying along the south coast of Western Japan begins to move northward and heavy rainfalls occur all over Western Japan especially over the southern part of Kinki district and the eastern part of Shikoku. Fig. 13 shows the 4-day mean 500 mb height pattern for 20~23 June, which indicates the developed trough extending from the eastern Siberia to the East China Sea and the ridge over the Sea of Okhotsk.

Example 6. For 13~14 August 1960, weak typhoons 6011 and 6012 landing at Shikoku run successively through Western Japan north-eastward. Consequently the south-south-west current in the lower troposphere prevails locally over the Kii Straits and heavy rainfall extends from Osaka Bay to the central part of Kyoto prefecture. Such a local current pattern will be described in the following section. Fig. 14 shows the 4-day mean 500 mb height pattern for 12~15 August. In this figure the long wave in the upper troposphere is considerably zonal and the two troughs of short waves move smoothly eastward, in front of which the two weak typhoons move north-eastward along the contour line respectively. So in this case the height pattern and the distribution of rainfall differ somewhat from those in the other cases of broader heavy rainfall.

Example 7. This heavy rain caused by the Baiu front having a long duration, 24~29 June 1961, spreads out over most of Japan. In Fig. 15 indicating the 4-day mean 500 mb height pattern for 25~28 June, as the deep trough of long wave extends from the eastern Siberia to Kyushu and the ridge is over the area of the Sea of Okhotsk, the trough of the short wave stays noticeably in the Far East.

Example 8. This case is for 27~28, October 1961 (in autumn). As a cyclone being generated over the adjacent seas south-west of Kyushu moves very slowly east-north-eastward, heavy rainfall occurs all over Western Japan. Fig. 16 shows the 4-day mean 500 mb height pattern for 26~29 October, which shows a very deep trough of long wave over Western Japan and the ridge over the vicinity of the Kamchatka Peninsula. Consequently the movement of the short wave is very slow.

Example 9. On 9 July 1967, heavy rainfall occurs all over Western Japan for a short time. This heavy rainfall we will discuss later. Fig. 17 shows the 4-day mean 500 mb height pattern for 7~10 July, which indicates intensely cold air coming from the Sea of Okhotsk and a trough of long wave over the East China Sea.

Comparing the nine examples above with each other, most of them have common features in the upper long wave pattern even for different seasons. That is, the deep trough of the long wave is located over the area from the

East China Sea to Kyushu. Most ridges of long waves are located over the area from the adjacent seas east of Japan to the Sea of Okhotsk or the Kamchatka Peninsula, and the remainder are located over the area from Hokkaido to eastern Siberia. When heavy rainfall occurs for a relatively long time, the trough and ridge are so intense that the blocking pattern is formed in the upper troposphere. While in the case of heavy rainfall for a short time, such as in examples 3, 6 and 9, the amplitudes of long waves are rather small. In the latter three cases cold air comes into the vicinity of the Kamchatka Peninsula, while in the former cases cold air comes down due south from the vicinity of Siberia in the direction of Korea.

## 4. The Rainfall around Osaka Bay

It is empirically known that in the Kinki, Chugoku and Shikoku districts heavy rainfall in the warm season often occurs over the north side of Osaka Bay, Awaji Island corresponding to the end of the Kii Strait and the region near the northern end of the Bungo Strait except for the rainiest areas facing the Pacific Ocean in Shikoku and the Kii Peninsula.

Here we investigate heavy rainfall around Osaka Bay. Three courses could be thought of the unstable humid current to flow into this area while keeping its instability. The first one is the course through the Kii Strait in the case of a south-south-westerly to south-westerly current, the second one is through the Seto Inland Sea in the case of a west-south-westerly current, and the last one is along the River Yodo in the case of north-easterly current. In the last case rainfall is not so heavy compared to the former two, so we shall discuss only the former two. In these cases the axes of heavy rainfall (or rain bands) extend from the vicinity of Osaka Bay nearly in the direction of the Lake Biwa. Examples are shown in Fig. 18 of the distribution of 24-hour precipitation (in mm). In such cases nearly south-westerly currents prevail in the lower troposphere and warm, moist and statically unstable air (wet tongue) flows into this region through the Kii Strait. From this point of view we would like to take four cases from the nine examples and investigate the relations of meteorological and orographic factors to the heavy rainfalls in detail.

Case 1. 26～27 June 1957. As shown in Fig. 18 (d) there are two axes of maximum rainfall extending north-eastward from the vicinity of Osaka and Kobe. Fig. 19 is the 850 mb level chart at 21 LST showing the Baiu front across Japan, the typhoon over the East China Sea, the strong south-westerly wind and the inflow of warm moist air (indicated by the distribution of dew-point temperature) over this region. Heavy rain occurs in the morning of 27 June. The hourly rainfall distribution from 01 to 09 LST with the wind (the velocity in knots) at the height of 1.5 and 3.0 km at 03 LST and the wind at 850 mb and 700 mb level at 09 LST over Shionomisaki is shown in Fig. 20. In Fig. 20 the rainfall area extends east-north-eastward from the vicinity of Osaka. At about 06 LST it shifts to the area from the vicinity of Mt. Rokko in the direction of the north-east and remains until about 09 LST. Though it is not well known the time when the wind over the region changes, it is seems that the shift corresponds to the change in the wind direction from west-south-westerly at 03 LST to south-westerly at 09 LST. Such west-south-westerly wind may flow into

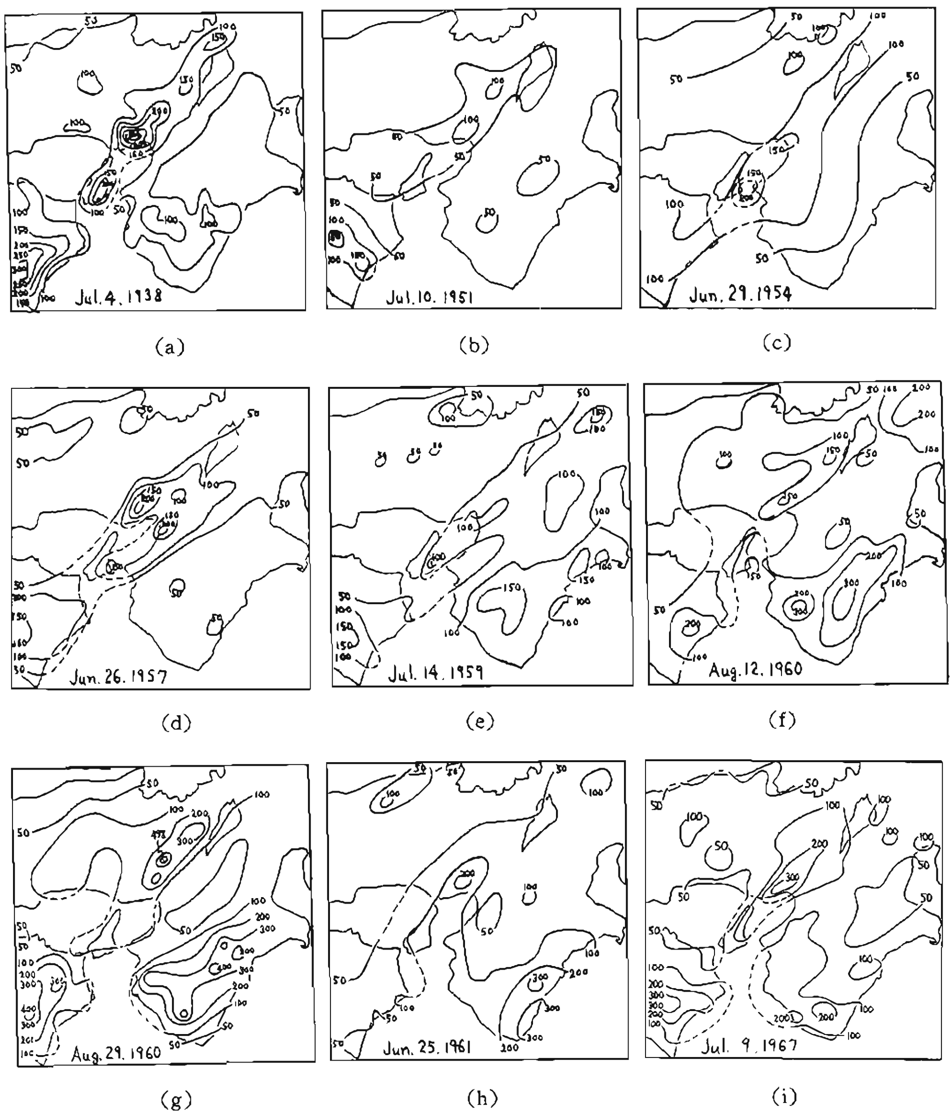


Fig. 18. The distribution of 24-hour precipitation in the Kinki district when heavy rain falls around Osaka Bay.

this region from the Seto Inland Sea.

Case 2. 29~30 August 1960. As shown in Fig. 18 (g) the rainfall axis is located from the vicinity of Mt. Rokko to west of Lake Biwa and the maximum precipitation is near 500 mm. Fig. 21 is the 850 mb chart at 21 LST, 29 August. After typhoon 6016 passes over Kochi (in Shikoku), Okayama and Tottori (in the Chugoku district) in the direction of north-north-east, a strong south-south-westerly wind persists over the region. The hourly rainfall distribution from

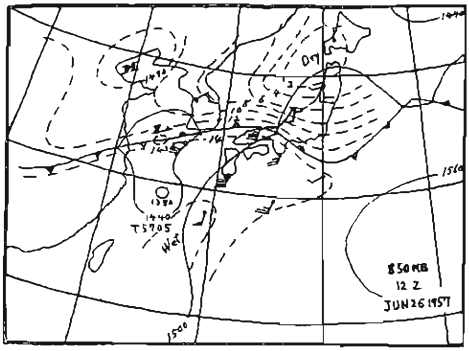


Fig. 19. 850 mb chart at 21 LST, 26 June 1957. Solid lines are contours, and dotted lines are isopleths of dew point temperature.

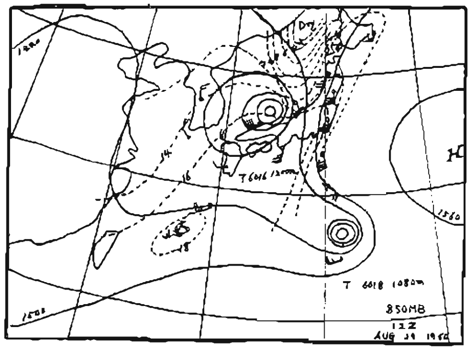


Fig. 21. Same as Fig. 19 but for 21 LST, 29 August 1960.

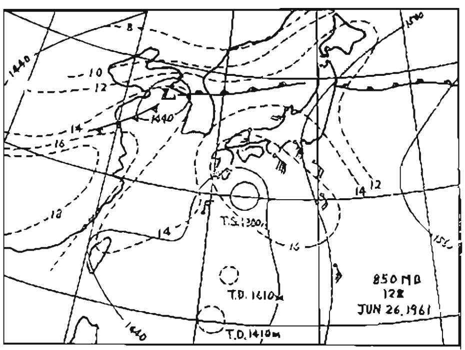


Fig. 25. Same as Fig. 19 but for 21 LST, 26 June 1961.

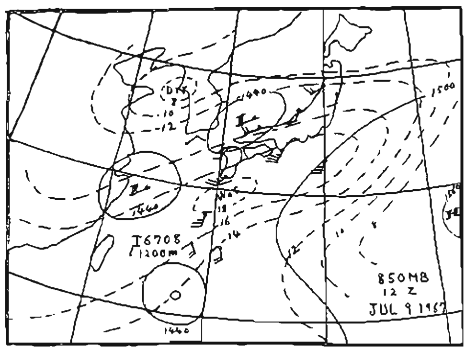


Fig. 26. Same as Fig. 19 but for 21 LST, 9 July 1967.

23 LST, 29 August to 07 LST, 30 August with the wind at 03 LST, 30 August is shown in Fig. 22. The hourly rainfall distribution is somewhat complicated until 03 LST, but after that the heavy rainfall remains over the area extending north-eastward from the vicinity of Mt. Rokko until 09 LST. Such a rainfall distribution is also seen by radar observation at 03 LST from Osaka as illustrated in Fig. 23.

Case 3. 26～27 June 1961. As described in Section 3 this heavy rain has long duration. In Fig. 18 (h) the rainfall distribution for 25 June is illustrated. We would like to study here the case of 26～27 June. Fig. 24 shows the hourly rainfall distribution for 01～09 LST, 27 June with the wind at 03 and 09 LST. The wind direction over Shionomisaki turns from south-easterly at 21 LST, 26 June to southerly and south-south-westerly at 03 and 09 LST, 27 June respectively. Correspondingly the rainfall area in the beginning located at the south-western part of Hyogo Prefecture moves eastward gradually intensifying and becomes heaviest at about 09 LST. Fig. 25 is the 850 mb level chart at 21 LST, 26 June showing the sufficient supply of moist air brought by a nearly southerly current. The direction and intensity of this current are influenced by three

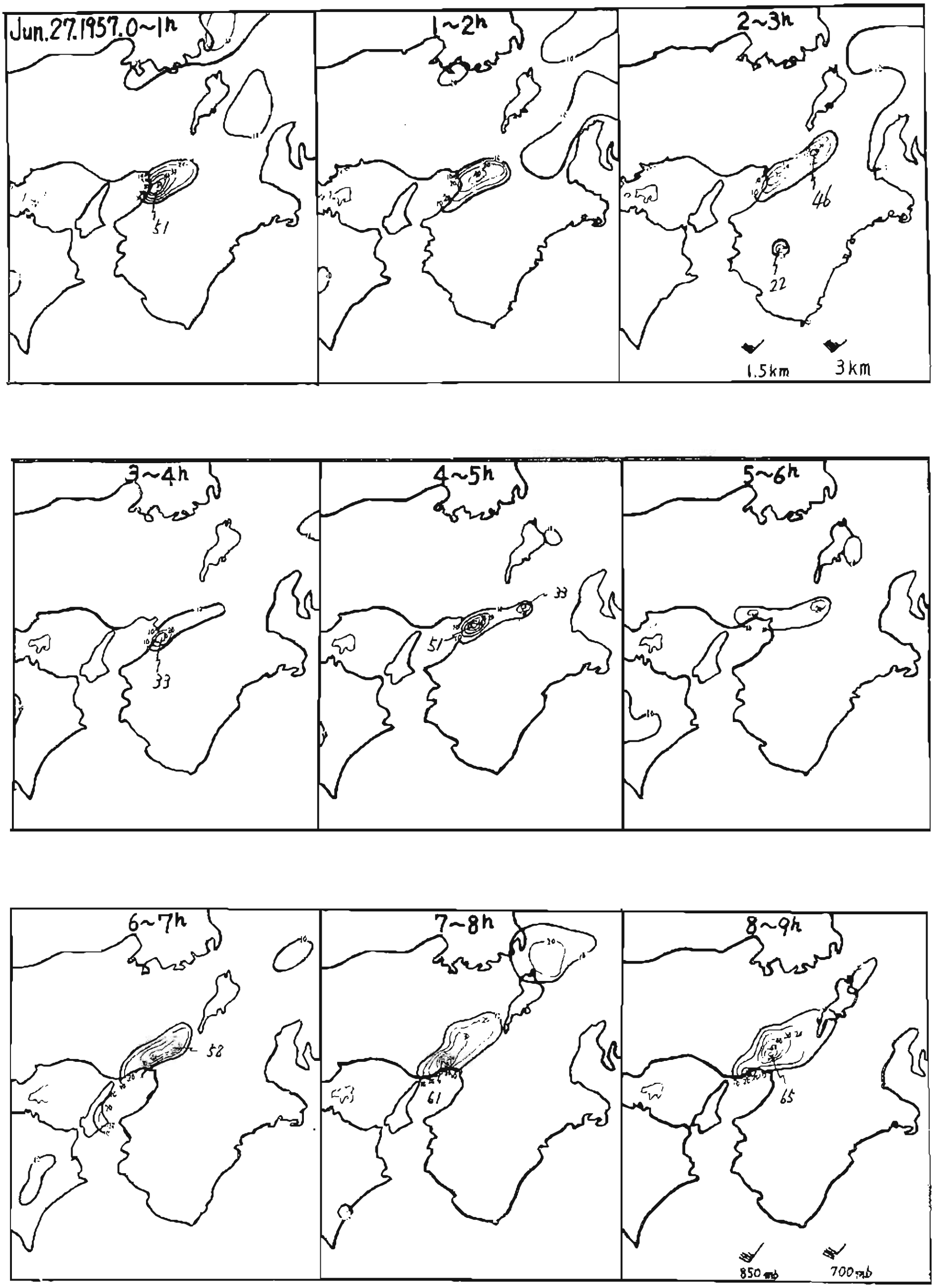


Fig. 20. The hourly rainfall distribution from 01 to 09 LST, 27 June 1957, with the wind (a long barb 10 knots) at the height of 1.5 and 3.0 km at 03 LST and the wind at 850 mb and 700 mb level at 09 and 21 LST.

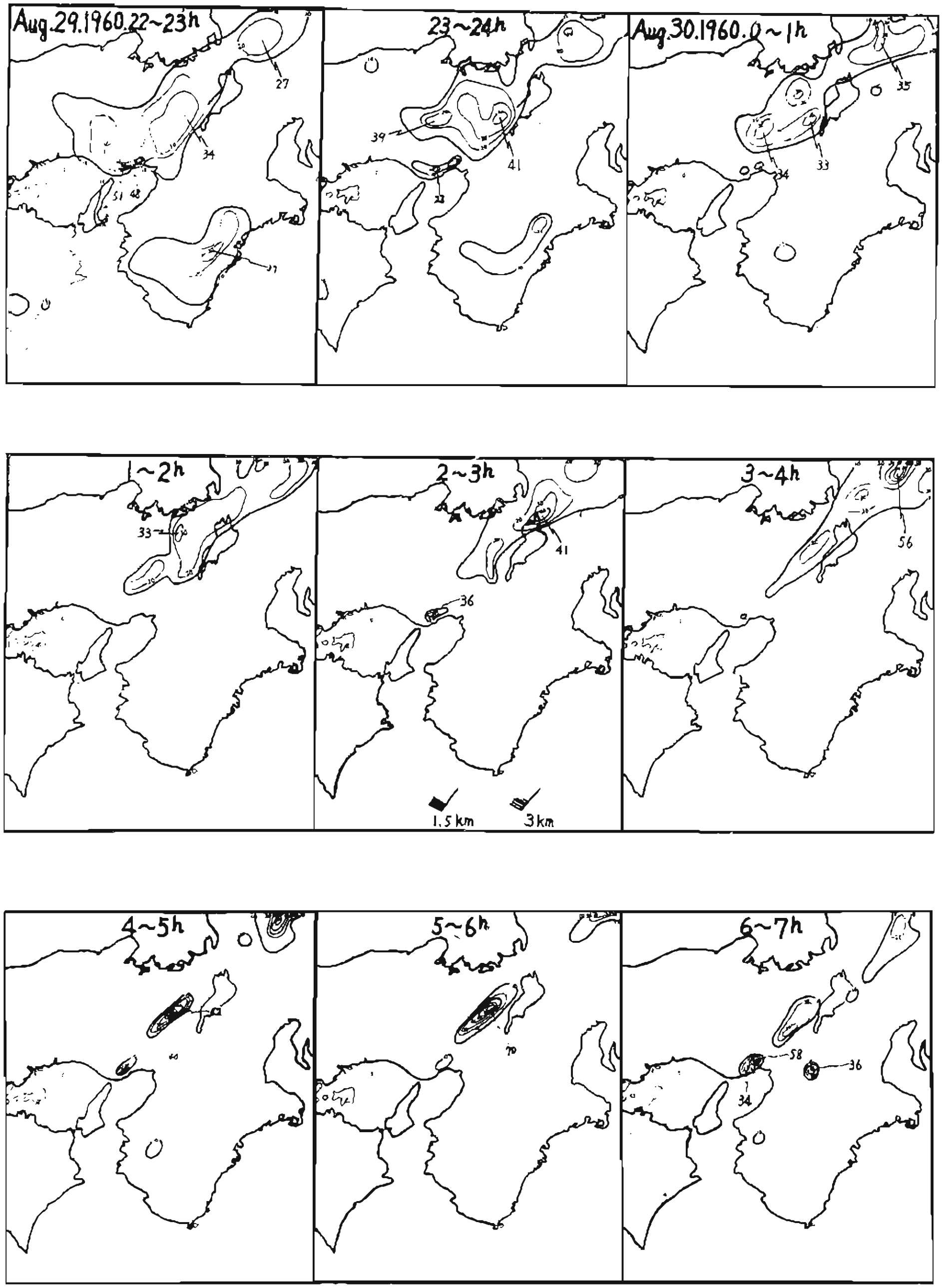


Fig. 22. Same as Fig. 20 but for 23 LST 29 to 07 LST 30, August 1960.

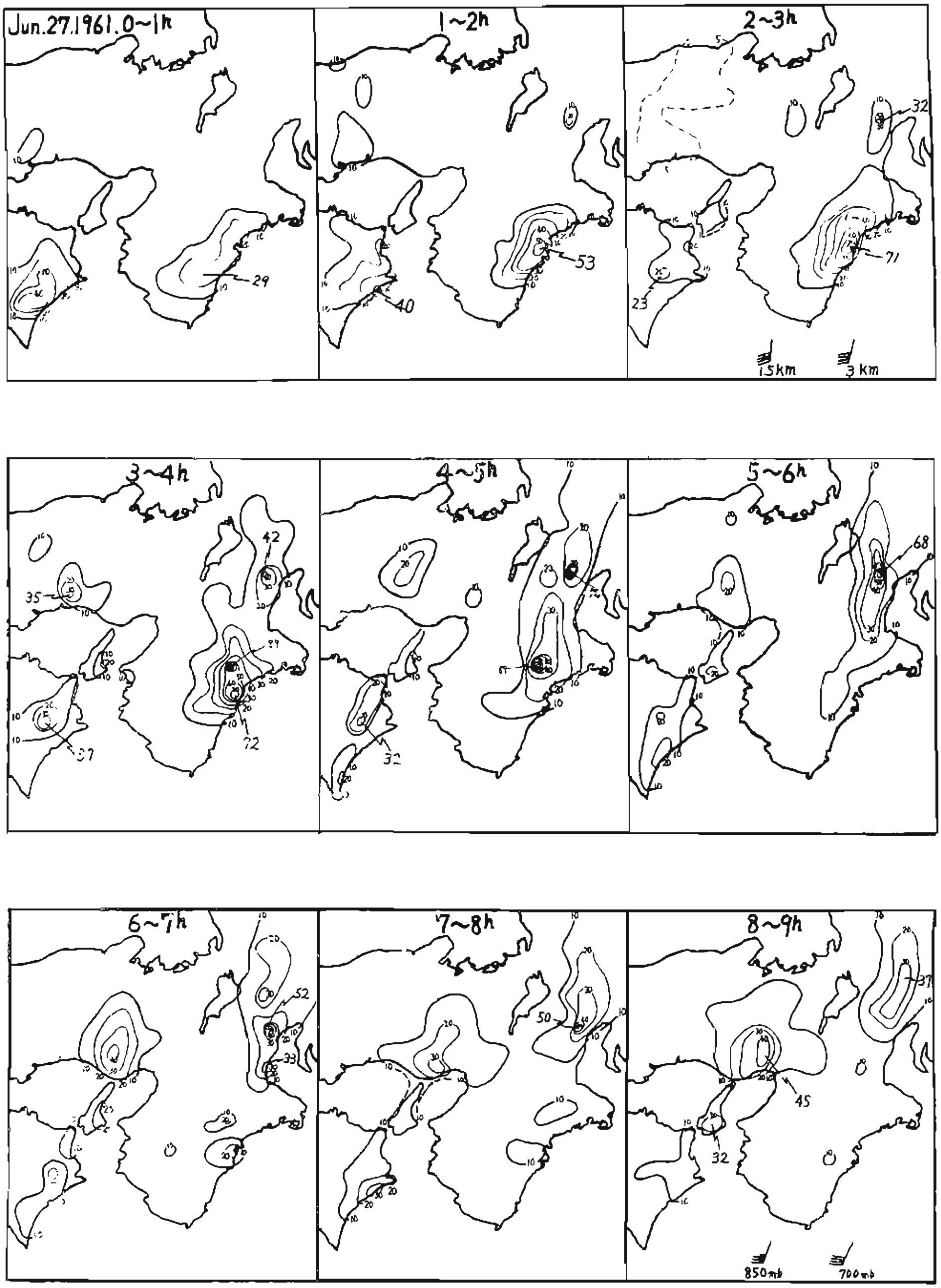


Fig. 24. Same as Fig. 20 but for 01 to 09 LST, 27 June 1961.

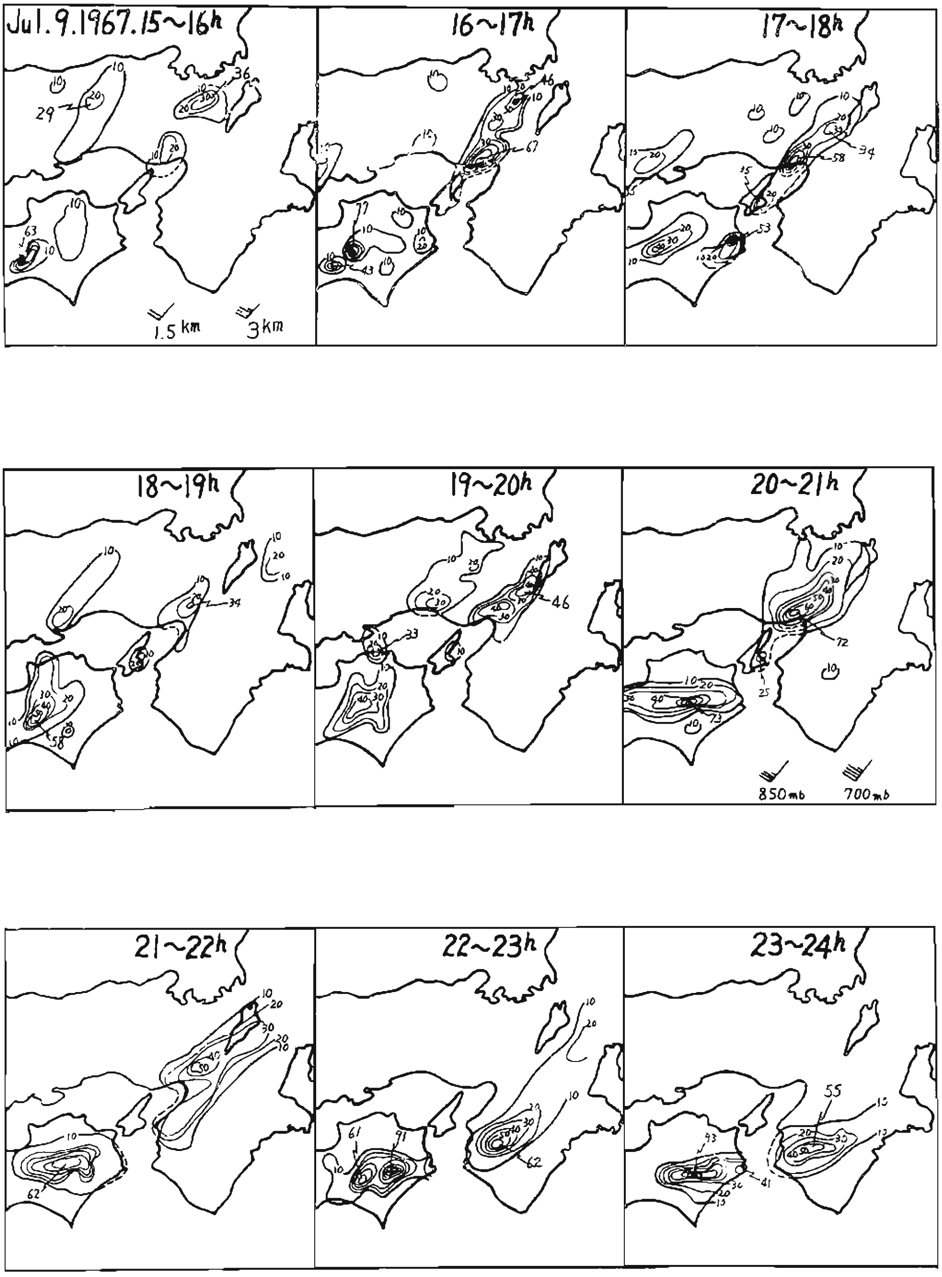


Fig. 27. Same as Fig. 20 but for 16 to 24 LST, 9 July 1967.

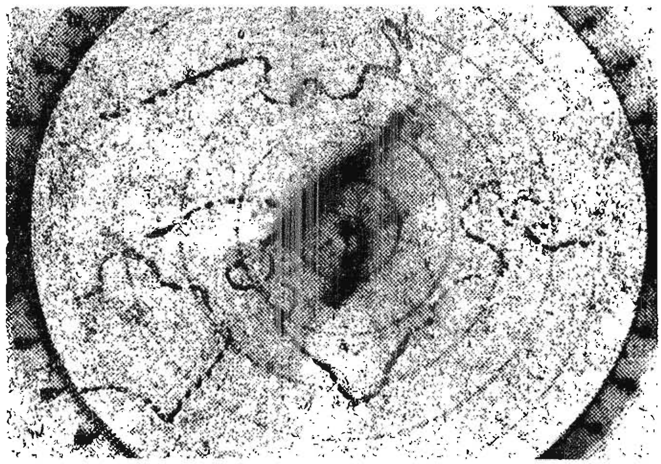

Fig. 23. PPI echoes (black) at 0300 LST, 30 August 1960 (3 cm radar, Osaka). Range markers 50 km intervals.

tropical cyclones.

Case 4. 9 July 1967[3]. As shown in Fig. 18 (i) the rainfall axis extends from the vicinity of Kobe to west of Lake Biwa and the maximum precipitation is more than 300 mm. Fig. 26 is the 850 mb chart at 21 LST, 9 July. The cyclone, decayed typhoon 6707, moves east-north-eastward along the coast of the Japan Sea passing over the vicinity of Oki Island with the strong south-westerly current over this region. The hourly rainfall distribution from 16 to 24 LST with the wind at 15 and 21 LST are shown in Fig. 27. The wind at Shionomisaki is constantly south-westerly. After about 13 LST the nearly stationary rainfall area extends north-eastward from north of Osaka Bay, and rainfall is intensified before 17 LST and weakend at about 19 LST and intensified again at about 21 LST. This intensification may be due to superposition of two rain bands, one of which has brought the heaviest rainfall over Western Japan and has moved eastward while weakening. In Fig. 28 the nearly stationary heavy rainfall area is shown by radar observation at 16h 29m LST from Nagoya. Echo cells are generated in the vicinity of the Kitan Channel and move north-eastward while growing. In this way heavy rainfall is brought over north of Osaka Bay.

In this region, since 1955 the number of cases of which 24-hour precipitation exceeds 200 mm is ten, and half of them, including the four examples described above, are cases in which a strong south-westerly wind prevails. But in most of the other examples the maxima of precipitations are located outside this region.

In conclusion, for the heavy rainfalls around Osaka Bay the prevalency of the strong south-westerly wind is necessary and the moisture is supplied through the Kii Strait or the Seto Inland Sea. The topography, such as the Kitan Channel, may play the role of a trigger releasing the static instability by converging the flow. As shown in the hourly rainfall distribution and by radar observation, such a rain band is about 100 km long and 20～30 km wide and remains at nearly the same place for a few hours or more.

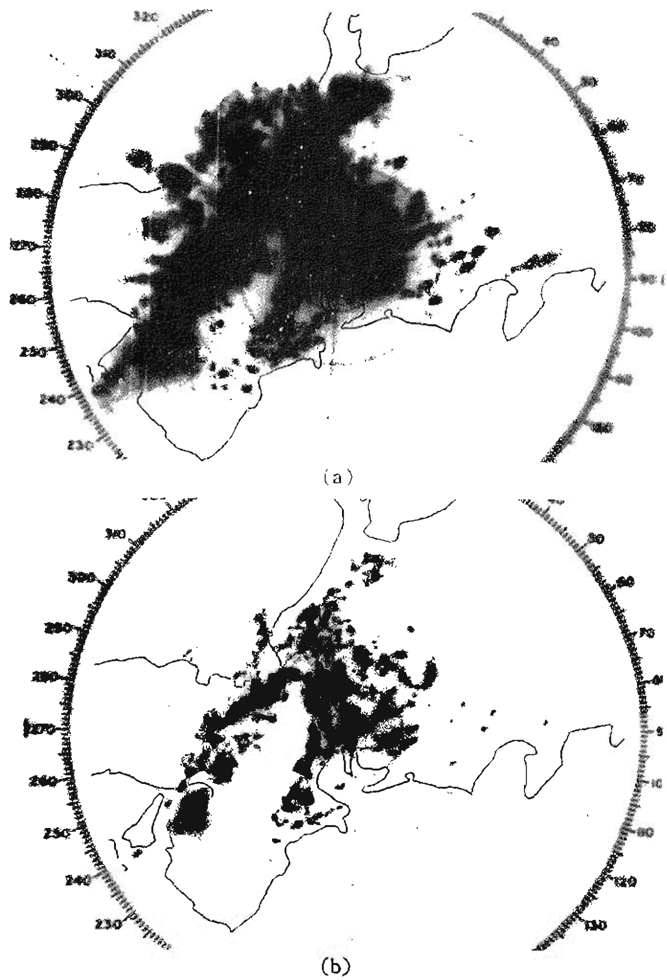


Fig. 28. PPI echoes (black) at 1629 LST, 9 July 1967 (5 cm radar, Nagoya). Range markers 50 km intervals. (a) weak echoes, (b) strong echoes.

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