For the Horizontal Convergent Fields of Heavy Rainfall in Early Summer

— Synoptic Analysis of the Heavy Rain for June, 1961 —

by

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Abstract

Late in June, 1961, a severe rainfall occurred in various places in Japan. The numerous data for the various meteorological elements for 12 levels of the troposphere during the heavy rain are adjusted and calculated by the electronic computer. The vertical structure of the heavy rain is analysed in detail. The large-scale pressure pattern of this heavy rain in the neighbourhood of Japan is similar to the typical pattern of heavy rain in early summer in the past. In case of heavy rain, the large-scale pressure pattern is such that the North Pacific high pressure is intense and the movement is stagnant or retrograde to westward in the lower layer of the troposphere. In the upper levels, the ridge over the North Pacific Ocean is similar to the pattern of the lower layer, and further, a typhoon appears over the sea to the south of the Japan Islands or a small-scale disturbance is formed over the Japan Islands. Such a pattern produces the most favorable conditions for the penetration of the strong southerly current into some area of the Japan Islands. In such a case, it is proposed for the vertical structure of the heavy rain that the north-south temperature gradient across the stationary Bai-u front and the subtropical or polar front is very large, and in the lower layer, a severe convergence exists along the stationary Bai-u front and also in the middle layer of the troposphere.

In the middle layer, the severe convergence is produced by the confluence of the general current of the westerlies or southwesterlies and the strong southerly current. The variation of the area of the severe convergence for the middle layer and the variation of the area of the heavy rainfall correspond remarkably to each other. The equation of conservation for potential temperature is lastly discussed.

1. Introduction

Among the forecast problems of meteorological phenomena in Japan, the forecast of heavy rain is one of the most important and difficult, ranking with the forecast of the cyclone and the typhoon and the longrange forecast. This is well borne out by the large number of papers on the synoptic analysis and forecast of heavy rain in the Bai-u season that have been accumulated since many years ago.

In the last week of June, 1961, a heavy rain occurred all over East-Japan, namely, Kinki, Chubu and Kanto districts with 200~300 mm for one day.

In June and July every year in the normal seasonal change of climate in Japan, a stationary east-west front is formed over central Japan along the boundary of the northerly current from the weak high pressure over the north of Japan Sea and the strong southerly current from the stationary high pressure over the Pacific Ocean in the lower layer of the troposphere. This front is called the Bai-u front among the meteorologists in Japan.

On the heavy rain of the last decade of June, 1961 the present authors (1963) have shown that the distribution of the observed 6 hours or 12 hours precipitation and the amount of the rainfall corresponds remarkably well to the estimated precipitation from the view point of meteorological dynamics. The estimated precipitation was calculated by means of the method proposed by K. GAMBO and his collaborators (1956). This method computes first the function of F which is called as condensation function, $F = \left[\left(-\frac{\partial q^*}{\partial P} \right)_T + \Gamma_P \left(\frac{\partial q^*}{\partial T} \right)_P \right]$ (q^* is the saturate mixing ratio, Γ_P is the lapse rate of adiabatic change) and the vertical current ω for each level of the atmosphere is multiplied to F , and then the result is integrated for the suitable thickness of the atmosphere and for the suitable time.

In this case, the authors (1) considered that the vertical current consists of three factors: the horizontal convergence of the lower layer of the atmosphere along the stationary Bai-u front for the dense observation of the ground surface and the slope of the mountain, namely the term V/FH (H is the height of the ground surface), and then the horizontal convergence for the large scale pattern for the middle and upper layers of the atmosphere on the rough network of aerological stations.

In this paper, the three-dimensional structure of the heavy rain for the last week of June, 1961, in Japan is analysed and discussed especially for the appearance of the front and the pattern of the convergence through cross section analysis along the longitude of 140°E.

2. Procedure of the synoptic analysis

The aerological stations used for the synoptic analysis are shown in Fig. 1, and the average distance of adjacent observatories is about 300 km. A map of Japan and its neighbourhood is shown in Fig. 2. In the synoptic analysis, the following meteorological factors are adjusted and computed by I.B.M. 704 electronic computer in the Meteorological Agency for each of levels 1000, 900, 850, 800, 700, 600, 500, 400, 350, 300, 250 and 200 mb, for 0900 and 2100 L.M.T. of seven days from 24 to 30 in June, for the following meteorological factors: geopotential height, temperature, humidity, dewpoint temperature, deficit temperature (the difference of the temperature and the dewpoint temperature), mixing ratio, potential temperature, static stability, equivalent potential temperature and the measure of the convective instability on the above levels at aerological stations in Japan and its neighbourhood.

Further, instead of the normal deviation for all the above meteorological elements, the deviation from the average value for a period of seven days from 24 to 30, is computed for 0900 and 2100 L.M.T..

Figs. 1~2. A map of East Japan and Aerological observatories in the neighbourhood of Japan.

In the first half of the period, namely, from 24 to 26 in June, no heavy rain occurred in Hokkaido, Tohoku and Kanto districts that correspond to the cross section analysis along 140°E , while in the latter half of the period, namely, from 27 to 29, heavy rain fall for three days continued in the Kanto, Tohoku districts.

The above two parts of the week from 24 to 30 are clearly distinguished for the amount of rainfall, and so the deviation from the average of the above meteorological elements will clarify the structure of the heavy rain.

The horizontal convergence for the large-scale pattern was calculated for the mesh size of two degrees of latitude and longitude for each level. The field of the wind is synoptically analysed from the observed wind for each level carefully. The convergence of the ground surface is calculated for the mesh size of 30 km from the observed wind for the dense network of surface observatories. The large-scale pattern of this period in the neighbourhood of Japan has been discussed in detail by the present authors (1). The sequential surface pressure pattern of the period for the heavy rain is shown in Fig. 3. For the surface pattern, the North Pacific high pressure gradually increases westward from about June 24 and its center displaced from 180°E to 170°E for 27 and then the center slowly weakened eastward from about 28. The fluctuation of the North Pacific ridge of the upper troposphere is also similar to the fluctuation of the surface pressure pattern. H.

(a) 26, 21.00

(b) 27, 09.00

(c) 27, 21.00

(d) 28, 09.00

(e) 28, 21.00

(f) 29, 09.00

Fig. 3. The surface pressure pattern of the period of heavy rain from 26 to 29 June, 1961, in the neighbourhood of Japan. (contour line: each 4 mb)

KATO (1963) reported the statistical result that the heavy rain of the Bai-u season in Japan occurs when the North Pacific High Pressure in the vicinity of 180°E increases remarkably. And so the large-scale pattern mentioned above is considered to be the general pattern of the heavy rain for the Bai-u season.

3. The cross section analysis of the heavy rain

The cross sections along 140°E are shown in Fig. 4, and they were analysed taking account of the observed wind, temperature, humidity, mixing ratio, potential temperature and their deviations from the time average for each level.

1) *The cross section of 26, 2100 L.M.T.*

The surface pressure pattern is shown in Fig. 3 and the tropical cyclone, 996 mb, advanced northward in 30°N and 133°E . The Bai-u front on the surface goes through the central part of the Japan Islands from east to west, and the North Pacific high pressure is displaced more southwestward than 12 hours before. On the level of 850 mb and 700 mb, the circulation near the tropical cyclone covers the Pacific coast of the Japan Islands. In the pattern of 500 mb level, the tropical cyclone is in the same position of the surface and a large-scale trough lies through the Korean peninsula with an inclination from NNE to SSW. The cross section along 140°E is shown in Fig. 4a. The Bai-u front is through Tateno (646) and Sendai (590) at the surface, Sendai and Akita (582) on 850 mb level and the vicinity of Akita on 800 mb level with such slope. The pre-front of the tropical cyclone is through Torishima (963) and Hachijojima (678) from the surface to 700 mb level and the general current in the atmosphere higher than 500 mb level to the north of Tateno is an WSW current and to the south of Tateno the general current is a warm current of SSW. The lower part of the polar front exists near Akita at 550 mb level, and front appears near Wakkanai (401) at 350 mb level. On the south side of this front, the deviation of the potential temperature shows $+3^{\circ}\text{C}$, but on the north side the deviation is negative. The polar front jet is near Sapporo (412) at 150~300 mb and the subtropical Jet is about Sendai at 150~250 mb.

The vertical structure of the horizontal convergence for the wind of the cross section along 140°E is shown in Fig. 5a. On Fig. 5, the various front is shown by the shadow. On the south side of the Bai-u front from the surface to 700 mb, there is a convergent area of $-2.0 \sim -2.8 \times 10^{-5} \text{S}^{-1}$ for about 37°N , and in the lower part of the polar front or in the upper part of the Bai-u front, there is a convergence of $-1.6 \times 10^{-5} \text{S}^{-1}$. For the low latitudes in $33^{\circ} \sim 35^{\circ}\text{N}$ for the layer of 350~500 mb, there is a strong convergence. This convergence is occurrent in the confluence of the general current of WSW and the other current of the southern wind. At this time, no heavy rain occurred along 140°E . It may be understood from all examples of Fig. 5 with the following analysis of the convergent patterns that the connection of the convergent part of the lower and middle layers of the troposphere is considered at first as an important factor, whether a heavy rain occurs or not. Secondly, it may also be understood from all examples of Fig. 4 with the following analysis of the cross section that the temperature difference of the warm air mass on the south and the cold air mass on the north side of the Bai-u front is also an important factor.

2) *The cross section of 27, 0900 L.M.T.*

In the surface pressure pattern of Fig. 3, the low depression is in the Kii peninsula and further the low depression extends to the Hokuriku and Shinetsu districts. The Bai-u front through Kii runs from east to west of the Japan islands.

Fig. 4. Meridional cross section along 140°E. Temperature isotherms are average for Potential-temperature with solid for plus deviation and cal front, stationary Bai-u front and other fronts. A short barb 100 knots.

Fig. 5. Meridional cross section of the horizontal convergence ($\partial u/\partial x + \partial v/\partial y$). dashed lines horizontal convergence. D, divergence; C, convergence.

shown with thick solid lines, thin lines signifying the deviation from the dashed line for minus deviation. Shadows show the polar front, subtropi- denotes 5 knots, a long one 10 knots, a triangle 50 knots and a rectangle

Shadows show various frontal-zones, thin solid lines horizontal divergence, (unit: 10^{-6} sec^{-1})

The tropical cyclone of 995 mb displaced more northward to 1° latitude than 12 hours before. The North Pacific high pressure is stagnant in the same position of 12 hours before. In the layer of 900~700 mb, the cyclone is formed near Wakasa Bay and in the layer of 600~400 mb, the small scale trough extends on the Kinki district with an inclination from NNE to SSW. The heavy rainfall occurs in the Kinki, Chubu and Kanto districts.

The cross section along 140°E is shown in Fig. 4b. The Bai-u front passes near Sendai at the ground surface, and at 850 mb level, through Hachiojima and Tateno, and near Akita at 600 mb level. The temperature gradient on both sides of the Bai-u front is distinctly seen. The lower jet by the strong southerly wind appears in Sendai, Tateno and Hachiojima toward the Bai-u front. The polar front is displaced a little southward, and pass near Sendai at 600 mb level and between Sapporo and Wakkanai at 350 mb level. On the south side of this front, the strong south-westerly current of warm air mass with a deviation of $+3^{\circ}\text{C}$ penetrates, and on the north side the westerly current of cold air mass with a deviation of -1°C blows. There is the polar Jet near Wakkanai in the layer of 175~250 mb with 120 knots, and the subtropical jet exists near Tateno at 150 mb level.

The vertical cross section of the horizontal convergence along 140°E is shown in Fig. 5b. Severe convergence appears near the Bai-u front where the southerly and the northerly currents are confluent. And the area of another severe convergence exists in the boundary layer between the lower part of the polar front and the upper part of the Bai-u front, the layer of 700~500 mb. The convergent pattern near the Bai-u front at the ground surface is shown in Fig. 6a.

There is severe convergence on the Kii peninsula of the Kinki district, Tokyo Bay and the Izu peninsula, in the south of the Kanto district.

3) *The cross section of 27, 2100 L.M.T.*

The low depression near Wakasa Bay at 0900 L.M.T. 27 proceeds to the northeast and develops into a cyclone of 1004 mb about Sendai at the ground surface, and the Bai-u front crosses the central part of Japan from the cyclone center. The tropical cyclone decreases and the North Pacific high pressure is in the same position in 12 hours before. The convergent pattern of the meso-scale at the ground surface is shown in Fig. 6b. The area of severe convergence exists along the Pacific coast of the south of the Tohoku district, Izu peninsula and Tokaido. A severe rainfall with 50~90 mm per 3 hours occurs in the central area of the Kanto district, Izu and Tokaido.

The vertical cross section along 140°E is shown in Fig. 4c, and the Bai-u front crosses between Tateno and Sendai at the ground surface, and at 600 mb level between Akita and Sapporo. The temperature gradient of the north and the south side of this front have a large difference. Namely, on both sides of the front, the deviation of the potential temperature has $+2^{\circ}\text{C}$ on the south side and a negative deviation on the north side. It may be considered that the frontal activity is intense. The polar front is displaced northward than 12 hours before, and the polar jet appears near Wakkanai at 200 mb level and the subtropical jet is near Akita at 150 mb level. The strong southerly current is prevailing from the middle to the upper layer of the troposphere and a severe rainfall occurs Tateno (646) with 90 mm/3 hours, and

it may be noteworthy that the very warm air mass penetrates in the troposphere higher than 400 mb level in Tatenno. This fact is discussed in 6 section.

The vertical cross section of the convergence along 140°E is shown in Fig. 5c. A severe convergence exists on the south side of the Bai-u front and it reaches to $-4.9 \times 10^{-5} \text{ S}^{-1}$ at 800 mb level at Tatenno. Further, a severe convergence appears in the middle layer of the troposphere, in the layer of 600~400 mb.

4) *The cross section of 28, 0900 L.M.T.*

The surface pressure pattern is shown in Fig. 3, the cyclone proceeds about Nemuro in Hokkaido and the Bai-u front running from its center to southwest extends to the central area of Japan with the depression, and there are a meso-high in the Chubu district on the north side of Tokaido with the heavy rainfall and the weak high pressure in Japan Sea. The northerly current from the high pressure over the Japan Sea and the southerly current from the North Pacific high pressure are confluent on the Bai-u front and a depression is formed from Hokkaido to Kyushu in the lower layer of the troposphere, from the ground surface to 700 mb level. A heavy rainfall occurs south of Kanto and Tokaido, with 50~80 mm per 3 hours.

The convergent pattern of the ground surface wind is shown Fig. 6c. And the maximum area of the convergence is in the Izu peninsula.

For the vertical cross section along 140°E of Fig. 4d, the temperature gradient between the north and the south side of the Bai-u front is very sharp. The polar and the subtropical front approach and pass near Tatenno at 500 mb level and about Sapporo at 250 mb level. The temperature at the back the front is very cold and the deviation of the potential temperature reaches -7°C in some places.

The subtropical jet appears about Akita, Sendai and Tatenno in the layer of 200~150 mb, and the polar jet seems like to be near Sapporo and Wakkanai in the layer of 200~175 mb.

The vertical cross section of the convergence along 140°E is shown in Fig. 5d, and a severe convergence appears on the south side of the Bai-u front, and other severe convergence exists in the lower part of the front in the middle layer of the troposphere. Another strong convergence appears in the upper layer on the south side of the front.

5) *The cross section of 28, 2100 L.M.T.*

The pressure pattern of the ground surface is shown in Fig. 3. The cyclone proceeds to the central part of the Kurile Islands and the Bai-u front running from its center to southwest crosses the central area of the Japan Islands, the depression covering the Japan Islands. The North Pacific high pressure proceeds eastward, decreasing its intensity. The distribution of the convergence of the ground surface is shown in Fig. 6d, and the maximum area of the convergence is about the center and south area of the Kanto district. The maximum area of rainfall is still the Izu and Boso peninsulas in the south of the Kanto district, about 90 mm per 3 hours.

For the vertical cross section of Fig. 4e, the tropical tropopause extends northward about Akita at 100~125 mb level, and from the middle layer to the upper layer of the troposphere, the subtropical front passes through about 500 mb level at Sendai

(a)

(b)

(c)

(d)

(c)

Fig. 6. The convergent pattern of the vicinity of the stationary Bai-u front in the lower layer for the troposphere (unit: 10^{-5} S^{-1}). Minus shows convergence, plus shows divergence and non-number is zero (non-divergence).

and at 250 mb level at Wakkanai. The Bai-u front crosses between Tateno and Sendai in the lower layer and the temperature gradient between the south and the north of the front is large. The subtropical Jet is near Akita at 175 mb level.

For the vertical cross section of the convergence in Fig. 5e, a severe convergence due to strong southerly wind exists on the south side of the Bai-u front and other severe convergence appears in the lower part of the subtropical front, in the middle layer of the troposphere.

6) The cross section of 29, 0900 L.M.T.

The surface pressure pattern is shown in Fig. 3 and the cyclone proceeds to the south of the Kamchatka peninsula and the Bai-u front running from its center extends over the Japan Islands, and the pressure pattern of the neighbourhood of Japan is the same in 12 hours before. The North Pacific high pressure proceeds eastward. In the layer of 900~850 mb, the depression is near Niigata (604) and in the layer of 800~600 mb, the depression is over the Japan Sea.

The pattern for the surface convergence of the meso-scale is shown in Fig. 6e. There is a severe convergence in the central Kanto district and the central Kinki district. The rainfall pattern resembles to the pattern of the surface convergence. Namely, a heavy rain occurs in the north of the Kanto and Chubu districts and in the central Kinki district with the amount of 50~70 mm per 3 hours.

The vertical cross section along 140°E is shown in Fig. 4f, and the subtropical front passes near Sendai at the 500 mb level, and at 250 mb level passes about Wakkanai, and a subtropical jet exists in Sapporo near 200 mb level. On the south side of the subtropical front the warm current predominates. A warm current with a deviation of $+4^{\circ}\text{C}$ penetrates into the south side of the Bai-u front.

The vertical cross section of the convergence along 140°E is shown in Fig. 5f. As in the previous case, the area of severe convergence exists on the south side of the Bai-u front, and a strong convergence appears in the lower part of the subtropical front in the middle layer of the troposphere, the layer of 700~500 mb.

As to the general character of the vertical cross section along 140°E of the above analysis, the vertical structure of the heavy rainfall in the Bai-u season is considered as the following.

In the lower layer of the troposphere, a warmer and stronger southerly current than the normal situation and the cold northerly current meet together near the Bai-u front and so a severe convergence is generated. And the warm air mass following this southerly current contains more moisture than an air mass of any other season in the neighbourhood of Japan. And the temperature gradient between the north and the south side along the Bai-u front is large and the frontal activity is intense.

The vertical current along the Bai-u front in the lower layer of the troposphere consists of the vertical motion due to the above convergence of the northerly and southerly currents and the vertical motion due to the central mountain system of the Japan Islands. Further, the severe convergence of the middle layer of the troposphere (i.e. the lower part of the subtropical front or the polar front) is vertically connected with the severe vertical current in the lower layer of the troposphere near the Bai-u front and so a severe vertical motion is formed throughout the entire troposphere.

4. The convergence for the middle layer of the troposphere and the pattern for the amount of precipitation of the heavy rainfall

The relationship of the horizontal convergence of the troposphere and the pattern of precipitation of the heavy rainfall is discussed in this section.

The time isopleth of the latitudinal profile along 140°E for the distribution of 6-hour precipitation during the heavy rain is shown in Fig. 7. The heavy rainfall with a precipitation of more than 50 mm per 6 hours continued from 0600 L.M.T. 27 to 1200 L.M.T. 29 in June, 1961. In Fig. 7, the time variation for the area of maximum rainfall is shown

Fig. 7. Time isopleth of meridional distribution for 6-hour precipitation along 140°E . Ordinate is latitude, abscissa is time sequence of 6-hour interval for the period of heavy rain, from 27 0600 L.M.T. to 29 1200 L.M.T. in June, 1961 (unit: mm/6 hours). Shadow of vertical strip shows the area of maximum amount of rainfall.

Fig. 8. Time isopleth of meridional distribution for horizontal convergence of the middle layer (arithmetic average of horizontal convergence for three levels of 600, 500 and 400 mb) along 140°E, unit: 10^{-5} sec^{-1} . Minus is convergence, plus is divergence. Thick line is the time sequence for the area of maximum convergence for meridional distribution.

Fig. 9. Time isopleth of meridional distribution for vertical currents of 500 mb-level along 140°E, unit: mb/h. Minus is upper current, plus is down current. Thick line is the time sequence for the area of the maximum upper current for meridional distribution.

by the shadow. In the first half of the period, the maximum rainfall appears in the north of the Kanto district, (i.e. in the higher latitude respectively) but in the latter half of the period, the area of maximum rainfall occurs in the south of the Kanto district, in the Boso peninsula and again the area of the maximum rainfall moves northward on the morning of 29.

The correspondence of the pattern of the time isopleths for the horizontal convergence or the vertical motion of each level for the troposphere and the pattern of the above rainfall was investigated in detail. The pattern of the time variation of the average convergence due to the arithmetic average of the convergence for the three levels of 600, 500 and 400 mb was most similar to the pattern of the time variation for the area of maximum rainfall. The time isopleth of such average convergence is shown in Fig. 8. In Fig. 8, in the first half of the period, the maximum area of convergence exists in the higher latitudes and in the latter half of the period, it moves in the lower latitudes and about 0900 L.M.T. of 29, it moves again northward, as in the pattern of Fig. 7.

The time variation of the vertical current for 500 mb level is shown in Fig. 9, and it does not resemble the time variation of the area of maximum rainfall in Fig. 7.

In conclusion, the authors would like to emphasize that of the rainfall mechanism of the heavy rain in the Bai-u season, the severe convergence of a large scale in the middle layer of the troposphere may be one of the main factors with the necessity of the

severe convergence of the warm moisture current and the cold current for the lower layer of the troposphere along the Bai-u front. K. MOHRI (1956) suggested also the above conclusion for one case of heavy rain in the Bai-u season.

Further, he showed that the variation of the jet stream on the subtropical front or the polar front and the variation of the area for the heavy rainfall are connected directly. H. RIHL (1962) also described the relationship of the variation of the jet stream and the distribution of rainfall, and proposed an analytic explanation of the mechanism.

In our analysis, the relationship between the variation of the jet stream and the distribution of heavy rain is not so directly clear as he says. There is only the fact that the appearance of the severe convergence in the middle layer of the troposphere and its variation are directly connected with the variation of the area of heavy rain. We have shown these circumstances above for the many cases of heavy rain and for the convergent field of 12 levels for the troposphere more in detail.

5. Pattern of the horizontal convergence and the atmospheric flow pattern

In this section, the authors discuss how the situation of the horizontal convergence, which is the most important in the heavy rain, will appear in the situation of the atmospheric flow.

The synoptic flow pattern of the lower layer of the atmosphere through the period of heavy rain is shown in Fig. 10. The pattern of all time shows that the strong southerly current with 30~45 knots and the northerly current are convergent near the Bai-u front. On the other hand, the convergent situation for the middle layer of the troposphere is shown in Fig. 11.

a) 27·0900: The polar front runs southwest from Hokkaido along the coast of the Japan Sea and a small-scale disturbance appears in the Chubu district. In such a pattern, the general flow of the neighbourhood of Japan has a westerly current, but on the coast of the Pacific Ocean to the east of the Kinki district, a strong SSW current penetrates and so a confluent area of two currents appears in the Kinki, Chubu and Kanto districts.

b) 27·2100: The general current of the neighbourhood of Japan has a westerly wind, and the strong southerly current from the Pacific high pressure increases owing to the small-scale disturbance in the Chubu district. The area of the confluence of the two currents appears in the Kinki, Chubu and Kanto districts.

c) 28·0900: In the middle layer for the neighbourhood of Japan, the westerly current predominates and the severe southerly wind near Hachijojima is confluent in the south of the Kanto district.

d) 28·2100: The general westerly current along the subtropical front blows and the southerly current from the Pacific high pressure is increased by the small-scale disturbance in the Kinki district, and two currents are confluent in the Kinki, Chubu and Kanto districts. A severe rainfall occurs in the area of this confluence.

e) 29·0900: The small-scale disturbance appears in the Kinki district and the general current of the westerlies along the subtropical front is confluent with the southwesterly current in Kinki, the north of the Chubu and Kanto districts.

Fig. 10. Large-scale flow pattern producing severe convergence in the lower layer of the troposphere; upper number: Height (m), low number: temperature ($^{\circ}\text{C}$).

As may be understood by the explanation of the above examples, the severe convergence in the middle layer of the troposphere is formed in the area of the confluence of the two currents of the general current of the westerlies or the south-westerlies and the strong southerly current from the Pacific high pressure. Especially, the southerly current is increasingly intensified by the appearance of the Typhoon on the ocean south of the Japan Islands for the large-scale pressure pattern or the appearance of the small-scale disturbance in the Japan Islands, and in such cases the convergence in the middle layer is further intensified.

Fig. 11. Large-scale flow pattern producing severe convergence in the middle layer of the troposphere; upper number: Height (m), low number: temperature ($^{\circ}\text{C}$).

6. The condensation heat and other problems

As pointed out in the analysis of the cross section along 140°E of Section 3, the air mass of the middle and upper layers at Tateno (646) was very warm and wet on 27, 2100 L.M.T. of Fig. 4c. Around 2100, L.M.T., a heavy rainfall occurred near Tateno and the amount of rainfall reached about 90 mm per 3 hours. For the mechanism to maintain such a warm air mass, the authors first examined the following thermodynamic considerations. The conservative equation of potential temperature is shown in the following:

$$\frac{d\theta}{dt} = \left(\frac{\partial\theta}{\partial t} + V\theta + \omega \frac{\partial\theta}{\partial p} \right) = \lambda \frac{\theta L}{c_p T} \Delta m$$

where θ is the potential temperature, V and ω are respectively the horizontal and vertical components of wind velocity, R is the gas constant for dry air, L is the latent heat, c_p is the specific heat of constant pressure for dry air, T is absolute temperature, Δm is the amount of liquid water condensed from water vapor per unit time ($\Delta m = -dq/dt$ with saturated specific humidity) and λ is a constant which is one or zero according to whether condensation occurs ($q \geq q_s$) or not ($q < q_s$).

In the assumption of a stationary state for a short period of 2 or 3 hours, the local change of potential temperature is neglected. And the results of the calculation for each term of the equation are shown in Table 1.

Table 1. Results calculated for each term of the conservative equation for Potential-temperature.

$$\frac{d\theta}{dt} = \left(\frac{\partial\theta}{\partial t} + V\theta + \omega \frac{\partial\theta}{\partial p} \right) = \lambda \frac{\theta L}{c_p T} \Delta m$$

$$\Delta m = -\frac{dq_s}{dt}$$

H	term	$V\theta$	$\omega \frac{\partial\theta}{\partial p}$	$\frac{d\theta}{dt}$	$\lambda \frac{\theta L}{c_p T} \Delta m$
	900 mb	-0.371	0.052	-0.319	0.207 ⁺
	850 mb	-0.267	0.144	-0.123	0.652 ⁺
	800 mb	-0.288	0.594	0.306	1.722 ⁺
	700 mb	0	2.400	2.400	3.584 ⁺
	600 mb	0	3.780	3.780	4.201 ⁺
	500 mb	-0.535	8.300	3.765	7.238 ⁻
	400 mb	-0.447	6.486	6.039	6.919 ⁺
	350 mb	0	7.428	7.428	5.407 ⁻
	300 mb	0	5.571	5.571	3.463 ⁻

(unit: °C/h)

In the lower layer, the condensation heat of the right-hand side of the equation is larger than the advective heating by the horizontal or vertical components and in the upper layer the condensation heat is smaller. For the results obtained by the above numerical analysis, the present author would like to consider that in the lower layer the evaporation due to the fall of the severe rain drops and the consideration of the small-scale vertical current due to the severe convergence on the ground surface cancel the excess of the condensation heat and in the upper layer the analytical error of the vertical current may be also entered into the results. For reference, the analysed results by Range Height Indicator and Plane Position Indicator of Radar of the observatory in the heavy rain are shown Fig. 12a, b. It has been analysed in detail according to Z. YANAGISAWA (1962).

In this case, the humidities of the upper layer about 300 mb level are also very moist and as may be seen from Fig. 12a, b, it is understood that the vertical current becomes remarkably in intense the upper layer.

However, the authors' analysis should be further investigated in many cases and more in detail.

Fig. 12. P.P.I. and R.H.I. echoes of June 27, 1961, obtained with a 3cm radar showing two isoecho contours. Left: 1727 L.M.T. June 27, (R.H.I.), Right 1717 L.M.T. (P.P.I.) June 27. azimuth 33°. After Z. YANAGISAWA.

7. Conclusion

The results of the foregoing sections can be summarized as follows.

1) In the aerological analysis of the various cross section and in others synoptic analysis, it may be effective to clarify the complicated mechanism in the near of the front that the analysis for the deviation from the suitable time mean of the various meteorological elements is also performed.

2) The large-scale synoptic pattern of the heavy rainfall in the last decade of June, 1961, in the Japan Islands is similar to the typical pattern of heavy rain in the past for the early Summer, and so the results of the analysis for this heavy rainfall have, general characteristics for the mechanism of the heavy rain.

The general aspect of the large-scale pressure pattern in the heavy rain is as the following.

In the lower layer of the troposphere, the North Pacific high pressure gradually develops and the movement is stagnant or retrograde. The ridge of the upper layer for the troposphere is also similar to the process of the variation of the North Pacific high pressure. And further, the typhoon appears on the sea south of the Japan Islands or the small-scale disturbance is formed over the Japan Islands and such a pattern produces the most favorable condition for the penetration of the strong southerly current, which brings the heat and moisture to the air mass in the neighbourhood of Japan.

3) In the period of the heavy rainfall, the temperature of the air mass on the north and south sides of the Bai-u front in the lower layer and of the subtropical

or the polar front in the middle layer of the troposphere deviate remarkably from the normal state.

4) The severe convergence of the middle layer of the troposphere (in the lower part of the subtropical or polar front) is vertically connected with the severe convergence in the lower layer of the troposphere along the stationary Bai-u front and then the strong vertical current is formed into the whole of the troposphere. It was shown that such vertical structure of the convergent field in the heavy rainfall is one of the most important and necessary factors in the mechanism of the heavy rain.

5) The north-south variation of the area of the heavy rain for the observed 6-hour precipitation and the north-south variation of the horizontal convergence in the middle layer (the mean of the convergence for three levels, 600, 500 and 400 mb in early Summer) are remarkably alike. This fact is the proof of the conclusion (4):

6) The convergent area of the middle layer corresponds to the area of the confluence of the general current of the westerlies or southwesterlies due to the large-scale pressure pattern in the neighbourhood of Japan and the strong southerly current mentioned by the condition of the conclusion (2).

The convergence of the lower layer along the Bai-u front is formed due to the convergence of the strong southerly current of the warm and moist air from the Pacific high pressure and the cold northerly current. Further, by the influence of the mountain system of the Japan Islands, a severe vertical motion is formed in the lower layer along the Bai-u front.

7) As a problem of the condensation heat, the equation for the conservation of the potential temperature was discussed. It is understood that the effect of the condensation heating should be considered thoroughly for the problems the severe rainfall. However, for this problem the analysis should be examined more in detail.

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梅雨期の豪雨の水平収斂場について

小 沢 正

36.6 豪雨すなわち、1961年6月下旬、東日本における豪雨について、対流圏を12の層にわけて、電子計算機を用い日本附近の高層観測所について、混合比、相等温位等を含む種々の気象要素を計算、整理し、また日本附近の緯度、経度2度毎の格子点での風の収斂量、上昇流を計算し、その構造を詳細に解析した。(豪雨の雨量に関する研究は別の論文にて報告)この豪雨の大規模な気圧配置は、過去の同期間の豪雨の典型的な pattern と類似しており、従ってこの解析結果は豪雨の機構について一般性をもつと考えられる。結果を要約すると次のごとくである。

1) 梅雨期の種々の断面図等の高層解析をするにあたって、種々の気象要素について、適宜の時間平均を作成し、その平均からの偏差について解析することは、複雑な前線附近の構造を捉える上に大いに役立つであろう。

2) 豪雨の際の大規模な気圧配置は、大気下層では北太平洋高気圧が発達し、その移動は停止するか、或いは西に逆行する。上層の北太平洋の ridge もまた下層と同様な変動経過を示し、なお日本南方海上の台風、或いは日本附近の小規模な擾乱の形成とあいまって、太平洋高気圧からの極めて温暖、湿潤な南寄りの気流の日本列島への強い流入の好条件をつくる。

3) 豪雨の際には、大気下層の梅雨前線、中層の subtropical front, polar front の南北の気塊の気温は、normal な状態より極めて偏奇し、強い南北気温傾度が形成される。

4) Subtropical front, polar front の下部、大気中層に強い収斂域が出現し、その収斂域が梅雨前線附近の大気下層の強い水平収斂と地形の影響とによる上昇流と結合して、大気全層にわたって、強い上昇流が形成されることが、豪雨が発生する機構の上に、重要な必要条件の一つであることが明らかにされた。

5) 140°E にそう実測の6時間降水量の豪雨域の南北変動と大気中層の水平収斂域の南北変動とが極めてよい対応がある。この事実は(4)の結論の証明となる。

6) 梅雨前線附近の大気下層の収斂域は、太平洋高気圧からの温暖多湿の強い南寄りの気流と北寄りの気流の収斂によって形成され、さらに日本中央山系の影響による上昇流と一体となって、大気下層で強い上昇流を形成する。大気中層の収斂域は大規模な気圧配置での西乃至南西の一般流と特に(2)で述べた条件による南寄りの気流の合流する地域に強い収斂が起り、大気下層の上昇流と結合して、大気全層にわたり強い上昇流が形成される。

7) 凝結熱に関する問題として、温位保存の式が検討されたが、豪雨の際には、凝結熱の効果は特に重視されるべきことを明らかにした。雨滴の蒸発、仮定、上昇流の計算誤差等の問題もあり、この問題に関しては、なお将来充分に検討されるべきであろう。