Dynamic Climatology of Atmospheric Circulation over East Asia centered in Japan

by

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Abstract

The present paper studies;

(i) the relationship between the weather in Japan and the upper-air circulations in East Asia which are classified into six flow types (Part I)

(ii) the synoptic processes and causes of the formation of blocking flow pattern in East Asia (part II)

(iii) the causes of Baiu in East Asia relating to the atmospheric circulation and the heat source near the Tibetan Plateau (part III)

The upper-air flow patterns in East Asia are classified into six kinds. They are high index zonal flow, trough flow, summer flow types (which bring about high temperature in Japan) and low index zonal flow, wave flow, blocking flow types (which bring about low temperature in Japan). In general, high index zonal flow, trough flow and blocking flow types bring about much rain, wave flow and low index zonal flow types little rain in Japan. And abnormal weathers in Japan are generally accompanied with the blocking flow pattern in East Asia.

Next, the synoptic processes that form a blocking flow pattern in the Shūrin and winter seasons are analysed. The former is responsible for the rainy season in Japan in early autumn and the latter for the cold NW-monsoon. A blocking flow pattern in the Shūrin season is initiated by the deformation of westerly flow which is given by a typhoon invasion into a westerly flow. This deformation is transferred downstream with a group velocity, resulting in the splitting of the westerly flow into two branches when the Shūrin season starts. Another blocking flow type in winter is caused by a large-scale heat exchange which is initiated by the development of a ridge over the Atlantic Ocean. With the development of this ridge, the polar air breaks out to Europe and America, resulting in the reinforcement of the ridges over the Asiatic Continent and the west coast of North America. These two ridges progress toward each other and finally fuse into one strong ridge, forming a blocking flow pattern in East Asia.

In early summer, Japan is visited by the Baiu season with a blocking flow pattern. The beginning of this season and the SW monsoon in India
have a close parallelism, and the stronger the monsoon low the stronger the Okhotsk sea high. Furthermore, the stronger the anticyclone over the Tibetan Plateau in early summer, the more predominant the blocking flow in East Asia. These statistical relationships are reexamined by a numerical experiment incorporating the effect of the atmospheric heat source and sink in early summer.

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1. Introduction

The climatological studies in Japan were started by such eminent meteorologists as K. Nakamura (1855–1929) and T. Okada (1874–1956). T. Okada published his voluminous “Climate of Japan” in English (1931), which may be considered a revised edition of Nakamura’s monograph. After that, E. Fukui (1938) published the valuable volume “Climate” in Japanese, in which he treated of many new subjects of climatology besides statistical climatology. With the development of observational study of the weather, the air-mass, the front and the motion of cyclones and anticyclones were introduced into climatology, and then a new climatology was started by T. Bergeron (1930), who insisted on the importance of the air-mass and wind systems. The study on these lines was first named “Dynamic Climatology” by him.

Dynamic climatology was started in this country by H. Arakawa (1932), who analyzed the characteristics of the air-mass in East Asia. K. Koenuma (1939) followed him with the study of the rainy season in Japan in the light of the movement of the front which runs between the continental and the maritime air-masses. K. Takahashi (1955) defined dynamic climatology as “the systematization of the weather phenomena on the basis of meteorology” and explained the successive transition of seasons by the passage of cyclones and anticyclones including the fronts. (1940).

After the War II, with the increase of world-wide upper-air observations, the surface pressure system, the air-mass and the surface front have been found to be steered by the upper-air flow. The dynamic climatology on the upper-atomosphere has been growing rapidly by using the long waves in westerlies, jet stream and a blocking anticyclone. K. Takahashi (1955) and the present writer (1955) classified the upper-air flow pattern in East Asia based on the weather in Japan and M. Yoshino
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(1965) published a detailed study of the Baiu season.

After the discovery of the blocking flow pattern in Europe by D. F. Rex (1950), the characteristic climate in Japan has been found to be closely associated with the blocking flow pattern in East Asia. T. Murakami (1951) made it clear that Baiu in Japan ends with the disappearance of the southern branch of westerlies flow. K. Suda and the present writer (1955) analyzed the formation of the blocking flow pattern in the Baiu season from a view point of the hemispheric westerly disturbances. H. Flohn (1957) and the Staff Members of the Academy Sinica, Peking (1957) found that the circulation over the Tibetan Plateau in summer has a close relation to the upper-air circulation in East Asia. K. Suda (1955) and A. Kurashima (1959) studied the winter monsoon in East Asia, pointing out that the cold-air outbreaks are associated with the meandering of the upper westerly flow.

However, these studies do not always have generality because they are confined to special cases and mostly treat of only the regional circulation in East Asia. The upper-air circulation in East Asia and the northern hemispheric interact on each other. And so the study of the northern hemispheric circulation is very important in understanding the climate in East Asia.

In the present study, the general relationship between the weather in Japan and the upper-air flow pattern in East Asia are studied from a view point of dynamic climatology (Part I). And then, the synoptic process to form a blocking flow pattern bringing forth the peculiar weather in Japan such as Shūrin and the cold air outbreak are studied synoptically and statistically by using the northern hemispheric upper-air charts (Part II). Lastly, Baiu and the cool summer in North Japan are studied with reference to the circulation over the Tibetan Plateau. The cause of the blocking pattern in the Baiu season is discussed by using the electronic high speed computer based on the atmospheric heat distribution (Part III).

Part I

Statistical relations between the upper-air flow pattern over East Asia and the “Grosswetter” or broad weather in Japan

1. The types of upper-air flow pattern in East Asia relating to the surface temperature

Changes of the season were studied by K. Takahashi (1941, 1955) based on the movement of anticyclone, cyclone and front. After War II, it has become clear that the surface anticyclone and cyclone are steered by the upper-air current, and a surface front is associated with the polar jet stream. These facts amply prove the importance of upper-air dynamic climatology which is now fast developing, as E. Fukui pointed out. (1961)

Relationship between mean surface temperature and mean upper-air charts has been studied by W. G. Leight, D. E. Martin (1949) and H. F. Hawkins (1950) in the U.S. However, it may not be too much to say that the present paper is the first study of the correlation between the anomaly of surface temperature and the anomaly pattern aloft in East Asia.
In this paper, 5-day mean 700 mb charts are classified into six types of flow patterns corresponding to the surface temperature distribution in Japan.

### 1.1 General relationship between the anomaly of 5-day mean 700 mb height and that of 5-day mean surface temperature

One may probably suppose that the surface temperature anomaly takes the same sign with that of 700 mb height, because the height at 700 mb level is determined approximately by surface temperature. We examined the above relation using the surface temperature anomalies at Sapporo, Tōkyō and Miyazaki and their 700 mb height anomalies for three years.

Table 1 shows the frequency (%) of the positive height anomaly at 700 mb being associated with the above-normal surface temperature. From this table we may conclude that this relation holds good for each season (about 70%), particularly at Tōkyō in winter and autumn but does not hold so good at Miyazaki in summer and winter (about 60%). On the other hand, for the negative height anomaly, the anomaly of surface temperature does not always take the same sign with that of 700 mb height and the relation between them is rather complicated as shown in Table 2.

<table>
<thead>
<tr>
<th>Season</th>
<th>Sapporo</th>
<th>Tōkyō</th>
<th>Miyazaki</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>70% (33)</td>
<td>85% (33)</td>
<td>60% (36.5)</td>
<td>71%</td>
</tr>
<tr>
<td>Spring</td>
<td>74 (35)</td>
<td>80 (38)</td>
<td>71 (40)</td>
<td>75</td>
</tr>
<tr>
<td>Summer</td>
<td>71 (31)</td>
<td>77 (34)</td>
<td>62 (42)</td>
<td>70</td>
</tr>
<tr>
<td>Autumn</td>
<td>68 (26)</td>
<td>85 (33)</td>
<td>75 (35)</td>
<td>76</td>
</tr>
<tr>
<td>Mean</td>
<td>71 (125)</td>
<td>82 (138)</td>
<td>67 (153.5)</td>
<td>73</td>
</tr>
</tbody>
</table>

Numbers in brackets indicate the actual frequencies.

<table>
<thead>
<tr>
<th>Season</th>
<th>Sapporo</th>
<th>Tōkyō</th>
<th>Miyazaki</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>54% (21)</td>
<td>38% (21)</td>
<td>65% (17.5)</td>
<td>53%</td>
</tr>
<tr>
<td>Spring</td>
<td>63 (17)</td>
<td>50 (14)</td>
<td>58 (12)</td>
<td>59</td>
</tr>
<tr>
<td>Summer</td>
<td>82 (22)</td>
<td>53 (11)</td>
<td>64 (11)</td>
<td>66</td>
</tr>
<tr>
<td>Autumn</td>
<td>67 (21)</td>
<td>50 (14)</td>
<td>42 (12)</td>
<td>52</td>
</tr>
<tr>
<td>Mean</td>
<td>67 (81)</td>
<td>48 (68)</td>
<td>58 (52.5)</td>
<td>58</td>
</tr>
</tbody>
</table>

Especially, a reverse relation is often found at Tokyo in winter. From Tables 1 and 2, we may conclude that the positive anomalies of 700 mb height are generally associated with those of surface temperature, while the negative ones of 700 mb height are not necessarily associated with those of surface temperature. That is, the signs of 700 mb height anomalies do not necessarily have the same signs as surface temperature anomalies.
To overcome this difficulty, dynamic climatological consideration is introduced here. As surface temperature is controlled mainly by the air-mass characteristics, the correlation ratios between the surface temperatures at Tokyo and the average heights of 700 mb surface over the air-mass source regions are calculated, and the results are shown in Table 3.

Table 3. Frequency (%) of the positive height anomaly at 700 mb over the air-mass source region being associated with the above-normal surface temperature at Tōkyō. Minus signs mean negative correlation.

<table>
<thead>
<tr>
<th>Season</th>
<th>Okhotsk Sea</th>
<th>Siberia</th>
<th>Ogasawara</th>
<th>Yang-Tze</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>−60%</td>
<td>−68%</td>
<td>72%</td>
<td>60%</td>
</tr>
<tr>
<td>Spring</td>
<td>58</td>
<td>54</td>
<td>81</td>
<td>78</td>
</tr>
<tr>
<td>Summer</td>
<td>−63</td>
<td>57</td>
<td>75</td>
<td>60</td>
</tr>
<tr>
<td>Autumn</td>
<td>56</td>
<td>−55</td>
<td>75</td>
<td>72</td>
</tr>
</tbody>
</table>

The air-masses which control the anomaly of surface temperature at Tōkyō are Ogasawara and Siberian air-masses in winter, Ogasawara and Yangtze air-masses in spring and autumn, Ogasawara and Okhotsk Sea air-masses in summer, respectively, and their source regions agree well with the centers of action for each season. For example, a warmer winter was observed when the Siberian air-mass was weak and the Ogasawara one strong. A cooler summer was observed when the Okhotsk Sea air-mass was strong and the Ogasawara one weak. Those distinct relations seem to show the importance of advection of air-masses for the temperature change in Japan.

Then the assumption that the north component of the anomaly flow at 700 mb level will bring on the below-normal surface temperature and the south component the above-normal is verified as shown in Table 4 and remarkable increases of percentages are found at Tōkyō (48-73%), at Miyazaki (58-72%), comparing Table 2 with 4.

Table 4. Frequency (%) of the negative height anomaly with the southerly wind being associated with above-normal surface temperature.

<table>
<thead>
<tr>
<th>Station</th>
<th>Sapporo</th>
<th>Tōkyō</th>
<th>Miyazaki</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>48%</td>
<td>63%</td>
<td>67%</td>
<td>58%</td>
</tr>
<tr>
<td>Spring</td>
<td>69</td>
<td>77</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>Summer</td>
<td>65</td>
<td>85</td>
<td>87</td>
<td>79</td>
</tr>
<tr>
<td>Autumn</td>
<td>72</td>
<td>67</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>Mean</td>
<td>63</td>
<td>73</td>
<td>72</td>
<td>69</td>
</tr>
</tbody>
</table>

From these results, we are inclined to conclude that the surface temperature anomaly in Japan is correlated to the large-scale upper flow pattern rather than to the height anomaly aloft.

1.2 Correlation fields of 5-day mean 700 mb height anomaly over East Asia and the 5-day mean surface temperature anomaly in Japan

A strong ridge, generally associated with a strong trough downstream, pushes
southward the cold air-mass over the Asiatic Continent bringing cold weather in Japan. Conversely, a weak ridge over the continent generally brings warm weather in Japan. In order to make clear this phenomenon qualitatively, the fields of correlation between the surface temperatures at Tōkyō and 700 mb heights at about twenty places in the environs of Japan were calculated and are shown in Fig. 1. Computations were carried out by using 5-day means for the four seasons of the years 1953–1955, and the correlation is expressed by the correlation ratio. These patterns show clearly that a strong negative correlation is associated with an area in the Asiatic continental high, a few thousand kilometers apart from Tōkyō, and a positive correlation is associated with the area of the Pacific anticyclone. These locations of the correlation centers change with the seasons coinciding with the action centers in each season.

In summer, for example, the correlation pattern (Fig. 1) shows that a cool summer prevails when the Okhotsk high develops and the Ogasawara high decays. The characteristics of the correlation pattern in every season are quite similar to those of the normal surface pattern in the corresponding season if we consider the correlation pattern as a pressure map, as will be stated in the following section.
It is interesting to see that the anomaly of surface temperature is much more closely correlated to the distant height anomaly at 700 mb level than to the height anomaly just overhead. The mean distance from a station in Japan to the center of positive correlation is about 1,500 km and the center of negative correlation about 2,500 km. The fact that the 5-day mean temperature in Japan is largely controlled by the anomaly height several thousand kilometers away is evidence enough to prove that the mean surface temperature is largely controlled by large-scale westerly disturbances. And the surface temperature anomaly can be estimated by using the height anomalies at the correlation centers as C.K. Stidd (1954) and K. Takenaga (1961) ascertained.

If we take surface stations further north, the correlation field also shifts northward as well as the correlation center, as shown in Fig. 2. The distance between the surface temperature station and the center of correlation field changes little with the displacement of the station. This may be due to the fact that the pattern of temperature anomaly is determined mainly by the relative position to the westerly wave as J. Namias (1953) stated.

1.3 Classification of the upper flow pattern in East Asia from a view point of surface temperature

The correlation maps between the 700 mb heights in East Asia and the surface temperature at Tōkyō for each season, as shown in Fig. 1, are classified into three flow types. By exchanging the sign in the three kinds of correlation map, six flow types are obtained in all. Comparing the above six flow types with the actual flow patterns in East Asia, the revised six flow patterns are arranged as shown in Fig. 3.
The characteristics of the six flow patterns are summarized as follows:

(a) High index zonal flow type \((Z_1)\)

The isobars run nearly zonal from west to east and the axis of the westerly flow is situated nearly at 45°N. This flow type frequently appears in spring and autumn and is accompanied with a moving anticyclone and a cyclone on the earth’s surface.

(b) Low index zonal flow type \((Z_2)\)

The isobars run nearly zonal as in the high index zonal flow but the axis of the westerly is situated south of 30°N. The westerlies, as a whole, shift further southward than with the high index zonal flow type and an anticyclone persists in the high
latitudes. This flow type is apt to appear in autumn and is associated with cold weather in Japan.

(c) Trough flow type (T)

The isobars run like a trough. This flow type appears mostly in winter, spring and autumn. In front of the trough, there flows a southwest wind which is associated with a surface front and high temperature. In the rear of the trough, there flows a northwest wind which is associated with a surface high of cold air.

(d) Wave flow type (W)

The isobars run like a wave with a ridge over the Asiatic Continent and a trough near Japan. This flow type appears in spring and autumn, and is associated with a surface pressure pattern of the winter type.

(e) Summer flow type (S)

The westerly retreating northward to 40°N and a subtropical anticyclone is predominant. A typhoon moves to the west in the low latitudes.

(f) Blocking flow type (B)

The anticyclone stagnates over the Okhotsk Sea and a trough over West Japan or the East China Sea. The westerlies are bifurcated into two branches, and the southern branch runs over Japan and the northern one runs north of the Okhotsk Sea, flowing together again to the south of the Bering Sea. This type of flow frequently appears in the Bäiu, Shūrin and winter seasons.

To study the relationship between surface temperature and the above flow types, the frequency of each flow type being associated with the temperature 2°C higher than and with the temperature 1°C lower than normal is calculated for each season at Sapporo, Tōkyō and Miyazaki.

The results are tabulated as follows:

<p>| Table 5. Frequency of flow types with high (upper) and low temperature (lower) for each season. |</p>
<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>T</th>
<th>Z₁</th>
<th>Z₂</th>
<th>W</th>
<th>S</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>34</td>
<td>12</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spring</td>
<td>36</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Summer</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Autumn</td>
<td>7</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>81</td>
<td>30</td>
<td>0</td>
<td>7</td>
<td>23</td>
<td>11</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>T</th>
<th>Z₁</th>
<th>Z₂</th>
<th>W</th>
<th>S</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Spring</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Summer</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Autumn</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>7</td>
<td>3</td>
<td>12</td>
<td>8</td>
<td>0</td>
<td>19</td>
<td>0</td>
</tr>
</tbody>
</table>
This table shows clearly that the flow patterns are to be classified into warmer and colder types. For example, warmer types are T and Z₁ types in the winter-half of the year, T and S types in the summer-half of the year, while the colder types are Z₂ and T type in the winter-half and B type in the summer-half, respectively.

As will be seen in Table 5, T and B types appear in both warmer and colder weather. This is to be explained by the relative position of Japan to the flow pattern.

For example, Fig. 4 shows the distribution of temperature anomaly relative to the trough. The origin of the coordinates is taken at the maximum curvature point of the trough, the ordinate the axis of the trough, the abscissa the distance measured on latitudes. The area of warm weather is found ahead of the trough and cold weather behind it. Temperatures more than 3°C above normal are observed at about 1,200 km southeast of the origin of the trough, and temperatures more than 2°C below normal are observed at about 800 km north of the origin of the trough. Accordingly, cold or warm weather is observed depending on the relative position to the trough. Similarly, high temperature is observed when a blocking flow type displaces northward resulting in warm air advection over Japan. Then, special attention should be paid to the direction of the upper-air flow for the estimation of surface temperature by using an upper-air flow type.

In sum, the upper-air flow patterns in East Asia are classified into six flow types by considering the mean surface temperature in Japan which is largely influenced by the large-scale upper flow pattern as verified by the correlation map.

The upper-air flow patterns of T, Z₁ and S types bring forth high temperature, while Z₂ and W types low temperature in Japan.
2. The types of upper-air flow patterns in East Asia relating to the precipitation in Japan

The surface cyclone is steered by the upper-air flow. Thus, precipitation as well as surface temperature is influenced by the upper-air flow pattern. However, the distribution of precipitation is largely affected by topography, resulting in rather complicated relations to the upper-air flow pattern.

In this section, the upper-air flow patterns in East Asia are classified from the viewpoint of precipitation in Japan.

2.1 Districts with a homogeneous character of precipitation

Climatic division in Japan has been studied by E. Fukui (1966), T. Sekiguchi (1955), T. Kawamura (1961) and many others. In the present paper, the broad scale climatic division is desirable, because we aim to clarify the relationship between the large-scale upper air flow pattern in East Asia and the precipitation in Japan. Much rain in Hokkaidō and little rain in Kyūshū are frequently experienced simultaneously. Therefore, to study the relationship between the upper-air flow pattern and the precipitation in Japan, it is necessary to study each of the climatic provinces separately.

By using the monthly total precipitation at Nemuro, Sapporo, Akita, Miyako, Sendai, Niigata, Kanazawa, Tōkyō, Matsumoto, Ōsaka, Shionomisaki, Kōchi, Hiroshima, Hamada, Kumamoto, and Miyazaki, the correlation coefficients between them are calculated with the help of M. Kuboki (1961). In this calculation, the cube root of the monthly total precipitation is used to normalize the precipitation.

From these calculations, the precipitation in winter is divided broadly into that of the Japan Sea side and that of the Pacific Ocean side, and the precipitation in Hokkaidō has no correlations with that in Honshū. It is interesting to note that the precipitation in the San-in district has no correlation (r=0.02) with the Hokuriku district, while showing a close relation (r=0.70) to the Kyūshū district.

By using these relations, the broad scale precipitation regions in Japan are established as follows. The number of these regions is three in winter, four in spring, three in Baiu, seven in summer, six in the Shūrin (or typhoon) season and three in autumn. The mean radii of these regions are 800 km in winter, 300 km in spring, 400 km in Baiu, 200 km in summer, 250 km in the Shūrin season and 400 km in autumn.

2.2 General relationship between the precipitation in Japan and the upper-air flow in East Asia

The relations between the upper-air flow pattern and the monthly total precipitation in the regions obtained above are summarized as follows:

i) Much rain falls in the Pacific Sea side when the positive height anomaly covers Japan in the winter-half of the year or the negative height anomaly in the summer-half. This means that the warm air invasion into Japan in winter or cold air invasion in summer brings much rain, because of the instability of the atmosphere.
ii) The upper southerly wind brings generally much rain while the upper northerly wind brings little rain.

Combining the above two rules, much rain falls in a district where an upper southerly wind flows in a positive height anomaly region in the winter half, while in the summer half, much rain falls in a district where an upper southerly wind flows in a negative height anomaly region.

Applying the above two rules to the actual atmospheric circulations aloft in East Asia, we classify the upper-air flow patterns from a view-point of the precipitation in Japan based on those defined in the previous section (Fig. 5).

![Classification of upper-air flow patterns](image)

(a) (b) (c) (d) (e)

Fig. 5. Classifications of upper-air flow patterns relating to the precipitation in Japan.
Much rain type

(i) Southwest flow type (SW)
In the winter half of the year, there flows a southwest wind in front of the trough. Under the southwest upper wind, a cyclone or a front passes causing precipitation.

(ii) Zonal westerly flow type (ZW)
As the zonal flow aloft is strong, the surface pressure system moves nearly in the zonal direction. A cyclone between two moving anticyclones moves through the warmer air bringing much precipitation in Japan.

(iii) Meridional flow type (M)
A blocking high stagnates to the north and a trough to the south of Japan. The southwest wind flows around the negative height anomaly over Japan and a stationary front runs under the southwest upper wind. This flow type brings much rain in the Baiu and Shūrin seasons and heavy snow in winter.

Little rain type

(i) Anticyclonic flow type (A)
The subtropical high develops and the positive height anomaly covers Japan. The surface Ogasawara high covers Japan, sometimes causing drought.

(ii) Northwest flow type (NW)
A ridge is on the Siberian Continent, a trough off the east coast of Japan, resulting in northwest wind over Japan. In consequence, dry weather is predominant in Japan.

As a typical example of the above flow types, the precipitation in winter and Baiu are discussed in the following sections.

2.3 Peculiarity of the upper-air flow pattern in East Asia from the viewpoint of the precipitation in Japan during winter

As mentioned in section 2.1, separate discussions of the Japan Sea side and the Pacific Ocean side are necessary with regard to winter precipitation.

1) Difference between the upper-air flow patterns for much rain and little rain in the Japan Sea side in winter

To make clear the difference of the upper-air flow patterns associated, respectively,

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Table 6. Precipitation ratio to the normal (%) used for the composite maps for above (upper) and below normal (lower) precipitations observed at Niigata and Kanazawa in winter.
with much rain and little rain in the Japan Sea side, the composite maps for both cases are analyzed by using the monthly mean northern hemisphere 500 mb charts. The data used for the composite map is shown in Table 6.

The composite maps thus constructed are shown in Fig. 6 and Fig. 7 for much rain and little rain respectively. Comparisons of the above two maps are summarized in the following:

<table>
<thead>
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<th>Much rain</th>
<th>Little rain</th>
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<tr>
<td>(i) M type and cold vortex develops over the Japan Sea</td>
<td>(i) ZW type with no cold vortex over the Japan Sea</td>
</tr>
<tr>
<td>(ii) Strong trough over the Japan Sea; SW wind flows with negative height anomaly</td>
<td>(ii) Weak flat trough over Japan; strong zonal wind flows with positive height anomaly</td>
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<tr>
<td>(iii) Polar vortex expands to the south causing a strong ridge over the Taimyr Peninsula corresponding to the strong Siberian high</td>
<td>(iii) Polar vortex shrinks around the North Pole causing a weak ridge over the Taimyr Peninsula corresponding to the weak Siberian high</td>
</tr>
<tr>
<td>(iv) Ridge over Central Asia with troughs over Europe and North America</td>
<td>(iv) Trough over Central Asia with ridges over Europe and North America</td>
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It must be emphasized here that the local monthly total precipitation in Japan is closely related not only to the local circulation in East Asia but also to the hemispheric circulation.

To examine the generality of the results listed above, the correlation map (Fig. 8) between the monthly mean northern hemisphere 500 mb heights and the cube root
of the monthly total precipitation in the Japan Sea side is calculated for the winters of 1946–1960 (n=45). As will be seen in Fig. 8, the correlation map shows a pattern quite similar to Fig. 6 and reverse to Fig. 7. That is, the peculiarity of the flow pattern obtained from the composite maps seems to have generality.

In general, the correlation map with the upper-flow pattern can be analysed in the same way as the composite difference map for the following reason.

The correlation coefficient is expressed by using a normal notation.

$$r = \frac{m}{\sigma_R \sigma_R'} \sum_{i=1}^{m} \frac{R_i - \bar{R}}{\sigma_R} \left( \sum R_i' - \bar{R}' \right)$$

Neglecting the second term which is generally small in magnitude,

$$= \frac{m}{\sigma_R \sigma_R'} \left( \sum R_i' - \bar{R}' \right) \left( \sum R_i - \bar{R} \right)$$

where \( R_i' \) the mean amount of much rain and little rain respectively, and we assume \( R_i'/R_i = -1 \).

The last term in the brackets is the composite difference value, and so the correlation map can be analysed in the same fashion as the composite map.
2) Difference between the upper air flow patterns for much rain and little rain in the Pacific Ocean side of Japan during winter

In the same way as in the previous section, the correlation map for the monthly total precipitation at Tōkyō during the winter is presented in Fig. 9. As is shown in Fig. 9, a large positive correlation area covers the region from the Central Pacific Ocean to Japan and a negative correlation covers the northeast of Siberia. The synoptic meaning of this is that the ridge over the Pacific Ocean develops while the one over the Asiatic Continent decays, resulting in a southerly wind flow with the maritime air-mass over Japan bringing much rain in the Pacific Ocean side of Japan. Inversely, when the trough over the Pacific Ocean and the ridge over the Asiatic Continent develop, a strong northwesterly flow over the Asiatic Continent will steer the polar continental air-mass to Japan, resulting in clear and dry weather in the Pacific Ocean side of Japan.

Fig. 9. Same as Fig. 8, but for the precipitation at Tokyo.

2.4 Peculiarity of the upper-air flow pattern in East Asia from the view-point of the precipitation in Japan during Baiu

As mentioned in section 2.1, there are three provinces to be distinguished in Japan in the Baiu season. Three representative stations of Sapporo, Sendai and Hiroshima are selected for North, East and West Japan respectively.

1) Synoptic consideration of the correlation fields in the Baiu season

The correlation maps for the total precipitation in the Baiu season at Sapporo, Sendai and Hiroshima are shown in Figs. 10–12, and the correlation profile between the mean zonal wind over East Asia (90°–170°E) and the total precipitation at the three stations is shown in Fig. 13–14.

By using Figs. 10–12 and 13–14, the synoptic meaning of the correlation fields
Fig. 10. Correlation map between the monthly mean 500 mb heights over the northern hemisphere and the monthly total precipitation at Sapporo in July for 1946-1960. For calculation of the correlation coefficients, the cube root of precipitation is used to normalize the distribution.

Fig. 11. Same as Fig. 10 but for Sendai.  
Fig. 12. Same as Fig. 10 but for Hiroshima.

for the three districts are summarized as follows:

1) North Japan

Much rain in North Japan is associated together with the strong subtropical anticyclone over the north Pacific Ocean and the strong trough over the Okhotsk Sea. As is shown in Fig. 12, the zonal wind in middle latitudes is stronger when much rain falls in North Japan and little rain in the rest of Japan. This means that the upper westerly advances to the north of 40°-50°N, and so the surface low steered by the upper westerly passes over North Japan in succession, while the rest of Japan is covered by the subtropical summer anticyclone with little rain.
(ii) East Japan and West Japan

As shown in Fig. 11, the precipitation in Honshū has a positive correlation \( r = 0.74 \) in July with 500 mb height over the Okhotsk Sea, a negative correlation \( r = -0.57 \) with the one over Japan and a positive correlation \( r = 0.74 \) with the one over the sea south of Japan. This flow type is a typical M type. The northern positive correlation area corresponds to the Okhotsk Sea high and the southern one to the Ogasawara high, the negative area over Japan to the Baiu front. Then the stronger the Okhotsk Sea and the Ogasawara high, the more precipitation falls in Honshū, because the air currents from the north and the south converge over Japan, as K. TAKAHASHI, M. HIROSE and the present winter’s analysis of extraordinary heavy rains at the end of Baiu season (1954).

Furthermore, the relationship to the zonal mean wind, as presented in Fig. 14, shows that much rain falls when the upper westerlies bifurcate into two branches. This flow type is the typical one in the Baiu season as pointed out by T. MURAKAMI (1951). The largest positive correlation at 30°N means that the stronger the southern branch of westerlies the more rain falls in Honshū, because the surface cyclone progressing on the Baiu front is controlled by the southern branch of the westerlies.

As stated in section 2.1, East Japan and West Japan are the other climatological provinces in the Baiu season. The difference of the flow pattern between them is clearly reflected on the broad scale correlation fields.

For example, comparing the correlation maps for East and West Japan (Figs. 11–12), one can easily find that a reversed correlation field is formed from Central Asia to North America, though little difference is formed over East Asia. That is, the wave pattern with a trough over the Atlantic Ocean, another over Europe and a ridge
over Central Asia brings much rain in West Japan and little rain in East Japan. And the reverse wave pattern brings little rain in West Japan and much rain in East Japan.

The above-mentioned two flow patterns are nearly the same as A. A. Girs' circulation model, which was introduced in Japan by K. Suda (1955). He classified the hemispheric circulation into the zonal and meridional flow types, the latter again divided into two types of flow named E-type and C-type. The former correlation profile corresponds to the C-type and the latter to the E-type. It is interesting to note that a slight difference in the flow pattern in East Asia is amplified over the

Fig. 15. Examples of upper-air flow patterns in East Asia associated with abnormal weather in Japan,
(a) Severe cold spring, heavy snow, heavy precipitation in Baju.
(b) Very warm spring, heavy precipitation in winter, drought in Baju.
Atlantic Ocean and Europe. This fact seems to suggest that the analysis of the hemispheric flow pattern is important for the understanding of the flow pattern in East Asia.

It seems important to pay attention to the fact that abnormal weather in Japan usually goes with peculiar flow patterns. For example, for severe cold weather (21–25 Apr. 1965), heavy snowfall (31 Jan. 4–Feb. 1963) and heavy precipitation (5–9. Jun. 1966) in the Baiu season, the upper flow patterns have the common feature of the blocking flow type as shown in Fig. 15a. The upper flow patterns for the abnormal warm weather (11–15 Apr. 1964), heavy precipitation along the Pacific Ocean side of Japan in winter (11–15 Jan. 1964) and little rain in the Baiu season (15–19 Jun. 1962) also have the common feature of the zonal flow type as shown in Fig. 15b. It may, therefore, not be too much to say that the fundamental types for the weather in Japan are the above two flow types—blocking (meridional) and zonal flow types.

These characteristic upper flow patterns over East Asia can not exist independent of the upper westerlies over Europe and North America. For example, the correlation map (Fig. 16) between the winter temperature along the Pacific Ocean side of Japan and the 500 mb heights over the northern hemisphere (1946–1965) shows that a warmer winter was accompanied with the upper westerly wave train of ridge over the east of North America, trough over the Atlantic Ocean, ridge over Europe and trough over Central Asia.

Such a teleconnection in the northern hemisphere is a very important factor in synoptic climatology. For example, the warmer (colder) winters in Japan are apt to associate with the warmer (colder) winters in Central Europe as shown in Fig. 17.

Therefore, the following discussion is confined to the study of the process of the formation of peculiar flow patterns in East Asia from the view-point of the northern hemispheric upper-air flow.
Part II

Dynamic climatology on the formation of the characteristic upper-air flow
patterns in East Asia

1. On the formation of the blocking flow pattern in the Shūrin season

Two rainy seasons appear in Japan, one before and the other after summer. The one is the Baiu season appearing normally in June and the former half of July, and the other is the Shūrin season which normally begins in the middle of September lasting for about a month. In the latter season, Japan is sometimes dominated by abnormal coolness and persistent rain for a month as J. Kimura (1966) analysed. Because of its mainly agricultural and meteorological importance, studies on the Baiu season have been piled up and various theories proposed. K. Suda and the writer (1955) analysed the Baiu season in 1954 synoptically and pointed out that it has a close relationship with the world-wide stationary wave system. And A. Kurashima (1959) explained the summer weather in Japan from the summer monsoon in East Asia.

The weather in Shūrin has many characteristics in common with that in Baiu. In both seasons, a high pressure persists over the Okhotsk Sea and a stationary front runs along Japan on which barometric lows move in succession, bringing cold air advection from the northeast and causing persistent rainy weather and low temperature.

The Shūrin season coincides with the typhoon period. Typhoons born in low latitudes in this season often visit Japan or its neighbourhood and may help to deform the westerly flow. Sometimes the cold air over the Siberian Continent is induced to Japan in the rear of a typhoon and forms a stationary front along the northern margin of the Ogasawara high.

The study of the Shūrin season has been rather neglected as compared with the study of Baiu, mainly because of its less importance for agriculture. In the present
study, the broad scale flow conditions in August and September of 1951, 1952, 1957 when Shūrin appeared with striking intensity were analysed based on 5-day and 15-day mean northern hemisphere 500 mb charts with a view to elucidating the seasonal change of the global flow pattern.

1.1 Characteristic features of the pressure distributions during the hot summer and the cool shūrin season

In August 1951, record-breaking hotness prevailed all over Japan bringing a phenomenal good harvest of rice to the farmers in Japan. However, by the end of August 1951, the temperature began to fall and stayed below normal during September. The trend of 5-day mean temperature anomaly for various stations in East Asia, as shown in Fig. 18, tells clearly how long the high temperature persisted in August and the low temperature in September. The 5-day mean temperature fell suddenly in late August in closely coinciding with the appearance of Shūrin weather. The above peculiar temperature change is also reflected on the upper flow pattern. In a hot summer, as shown in Fig. 19a, an upper anticyclone covers Japan with its center in the south of the country and the upper westerlies retreat to the north (9–13 Aug. 1951). This flow type was classified as S-type in the preceding section. In a cool Shūrin season, however, the upper westerlies shift southward forming a trough over the Japan Sea.

Then, southwest wind flows over Japan proper, forming a high over the Okhotsk Sea, as seen in Fig. 19b. This flow type was classified as B-type in the preceding

![Fig. 18. 5-day mean temperature anomaly at one Saghalin and three Japanese stations for August and September, 1951.](image-url)
This type of blocking high often appears in the Baiu season with a tendency to persist as has been pointed out for the weather in 1954 by the writer. The surface pressure pattern accompanied by this blocking high is the "north high" situation with a stationary front (called Akisame Zensen) running along Japan between the warm Ogasawara and the cold Okhotsk air-mass which brings cold air advection from the northeast to Japan. These make up the characteristic surface pattern in the Shūrin season. To make clear the hemispheric change of the pattern which occurred simultaneously with the local pattern change described above, two 15-day mean maps centered on the hottest day in August (Fig. 20a) and the coldest day in September (Fig. 20b) were constructed for 500 mb level and, based on them, the characteristic features of the northern hemisphere flow pattern were studied. Marked characters of the westerly wave in summer could easily be found; four pronounced waves with ridges in eastern Europe, Japan, Canada and Iceland kept nearly the same
positions through August. Four stationary troughs ran between these ridges with negative height anomaly.

With the onset of Shūrin, the wave number of the westerly changed from four to three with ridges in Central Asia, the west coast of North America and Iceland.

It is important to note that there occurred the reversal of the flow pattern over the Asian Continent from summer to Shūrin. Namely, the ridge over Japan, which brought on warm summer weather there, gave place to a trough, the trough over Central Asia to a ridge and the ridge over eastern Europe to a trough, though little change was observed in the western hemisphere. Another characteristic feature is the positive height anomaly around the pole taking the place of the negative height anomaly in summer.

To make more clear the difference between them, the tendency chart was constructed using two 15-day mean 500 mb charts in summer and Shūrin. The chart thus constructed contains the normal tendency which it is desirable to exclude. The tendency chart from which the seasonal normal tendency was subtracted is shown in Fig. 21. This has a similar pattern to the height anomaly distribution in summer (Fig. 20a) though with opposite signs except over the North American Continent. The zones of negative height anomaly in summer centered at 0°E, 100°E and 150°W correspond to the zones of positive height tendency.

Fig. 21. Tendency chart constructed by subtracting 500 mb height in August from that in September excluding the normal tendency.

Fig. 22. Anomaly height of 500 mb along 60°N parallel in the Shūrin season of 1951.
To study how and when such a large-scale transformation of the wave system in the westerlies happened, the isopleths of the 5-day mean anomaly height profile along 60°N were constructed for August 4 to September 22 as shown in Fig. 22. Four pronounced ridges stagnated near 50°E, 140°E, 100°W, 40°W during summer in 1951, but changed into three waves in the middle of September. Three wave systems

Fig. 23. Same as Fig. 22 but for Shūrin in 1957.
having three ridges near 0°E, 100°E, 150°W remained stationary till the end of the Shūrin season. The above striking change in wave number from four to three was often observed in the Shūrin season (1953, 1955, 1956, 1957, 1964 and 1965) and one of them (1957) is shown in Fig. 23.

Thus, Shūrin weather should be understood as a link in the westerly wave trains rather than a local weather condition and this leads to the conclusion that the persistence of abnormal weather is nothing but a result of the stationary character of the westerly wave system.

The subject of the present problem is to analyse on a hemispheric scale the wave number of westerly changes from four to three in relation to the poleward shift of the positive height anomaly.

1.2 A great positive height anomaly around the pole as a cause of seasonal change in the flow pattern from summer to Shūrin

The seasonal change in the flow pattern from summer to Shūrin may be characterized by the decrease in wave number from four to three. In this section, the seasonal change in wave number is analysed synoptically relating to a great positive height anomaly around the pole.

The positive height anomaly on 500 mb level surrounding the pole began to increase in the last decade of August and reached its maximum in the first decade (1951) or the second decade (1957) of September. Then, it began to decrease as shown in Fig. 24a, b. The period of increasing positive height anomaly around the pole coincided well with the period of increasing kinetic energy of the north-south wind component. This seems to suggest that a large-scale exchange of air-mass between middle and higher latitudes occurred, as T. Ozawa (1957) and N. A. Phillips (1956) analysed.
To show more clearly the motion of positive height anomaly, the centers of positive height anomaly were traced on the 5-day mean 500 mb anomaly charts for Aug. 6th–10th (Fig. 25a). The full line shows the trace of the center of positive height anomaly, the broken line that of the center of negative height anomaly and the number within a circle the central day of the 5-day mean. As can easily be seen in this figure, the positive height anomalies situated over Japan, the west coast of North America and the Atlantic Ocean during the first half of August moved northward continuously and finally reached near the North pole on September 5th. Thus, they amalgamated near the North pole and developed into one great positive height anomaly covering the polar region, while the center of negative height anomaly situated over the Bering Sea and the Taimyr Peninsula displaced equatorward bringing cold air invasion to Japan.

Fig. 25a shows the amalgamated positive height anomaly which occupied the large area over the higher latitudes centering at the pole, but this situation did not last and burst southward in three branches as shown in Fig. 25a. These three branches were located over Central Asia, the west coast of North America and the Atlantic Ocean, where climatological anticyclogenesis develops as J. Namias (1951, 1964) stated.

In accordance with this sudden extension of positive height anomaly, the wave number in westerlies changed abruptly into three with three ridges. Nearly the same development of atmospheric circulation took place in the Shūrin season in 1957 as shown in Fig. 25b. The centers of positive height anomalies situated near Japan, the west coast of North America and the Atlantic Ocean progressed to the north and the centers of negative height anomalies over East Asia, the Bering Sea and East Canada progressed to the south. This means that a large-scale air-mass exchange between high and middle latitudes has taken place. This meridional exchange process is now considered as an important precursor of cold air outbreak in long-range weather
forecast. Thus the Shūrin season in Japan is closely connected with a hemispheric development of upper-air circulation.

1.3 Synoptic behavior of the circulation in the transition from summer to Shūrin

A large-scale meridional exchange of air-mass takes place when the geostrophic zonal westerly wind (averaged for each latitude circle between 25°N and 75°N) shifted equatorward as shown in Fig. 26. In this case, the zonal index (index of westerly wind speed expressed by zonal height difference between 40°N and 60°N. In this paper, however, the zonal index is expressed in m/sec.) declined markedly. Such a situation is called a low index. Other examples of low index in 1952 and 1957 are shown in Fig. 27, when a marked Shūrin season visited Japan. We must pay special attention to the fact that a low index appear some days after a typhoon invaded the westerlies. The equatorward shift of westerlies or low index, coinciding with the beginning of Shūrin, does not seem to occur at the same time everywhere in the northern hemisphere. For this study, the latitudinal profile of zonal geostrophic flow based on 5-day mean height was constructed along the meridians 180°E, 120°E and 60°E in 1951 and 1957, as shown in Fig. 28. As will be seen in this figure, the shift of the westerlies stated at 180°E for Aug. 24–28 followed by those at 120°E for Sep. 3–7, and at 60°E for Sep. 8–12 in 1951 as indicated by an arrow in Fig. 28a.

![Fig. 26. Isopleth of 5-day mean geostrophic zonal wind. (m/sec.).](image)

![Fig. 27. Zonal index (m/sec.) of westerly flow in 1952 and 1957.](image)
Fig. 28a. Isopleth of 5-day mean geostrophic zonal wind (m/sec.) along meridians 180°E, 120°E and 60°E in 1951.

Fig. 28b. Same as Fig. 28a but for Shūrin in 1957.

Fig. 29. Isothermal line of $-15^\circ$C on 500 mb surface from 26th August to 10th September.
The southward shift of the westerlies also appeared in Šūrīn of 1957 (Fig. 28b). There seems to be a favorable place for the shifting of the westerlies to the south. And it has a close relationship with the cold air surge shown by the equatorward shift of the isothermal line of $-15^\circ$C at 500 mb level (Fig. 29). The first surge of the cold air began in the Bering Sea just preceding the Šūrīn season, causing the westerlies to shift equatorward as mentioned above. It was followed by a consecutive surge of cold air over the Sea of Japan on 5th September and then another surge of cold air occurred in eastern Europe on 10th September. It is of some interest to note that the season went ahead in the east rather than in the west in the late summer of 1951 and 1957.

Some questions may be presented as to why such a consecutive shift of the cold air occurred. For this treatment, the flow patterns aloft were analysed, based on 5-day mean 500 mb charts. The chart for Aug. 14–18, not shown here but exhibiting a similar pattern to Fig. 19a, has characteristics of a typical summer type with the high pressure center stagnating over Japan and the low pressure center over the pole. The next chart for Aug. 19–23 shows a new trough formation over Korea which enclosed the severe typhoon Marge (954 mb) as shown in Fig. 30. With the penetration of the typhoon into the westerlies, its energy was damped rapidly but it transported a vast amount of warm air to the north along the upstream of the ridge.

Fig. 30. Series of 5-day mean 500 mb chart from summer to Šūrīn in 1951.  
(a) A typhoon invades into the westerly flow.  
(b) A ridge near the Okhotsk Sea and a trough over the Bering Sea are developing.  
(c) A ridge over the west coast of North America develops.  
(d) There forms a blocking flow pattern in East Asia, resulting in Šūrīn in Japan.
which caused the development of a ridge and trough downstream as can easily be understood by a barotropic vorticity consideration as computed by J.S. Winston (1955). With the continuous increase in amplitude of the ridge over the Okhotsk Sea as observed in the next chart for Aug. 24–28, the cold air over the Bering Sea was steered to the south and part of it began to invade northern Japan along the Kuril Islands. Then prevailing zonal westerlies began to meander and finally split into two branches over eastern Siberia as shown in Fig. 31. The southern branch ran over Sakhalin and the northern one over the North Polar Sea, confluencing again in the middle Pacific Ocean. The cold air which had stagnated over the Taimyr Peninsula before the jet stream split into two began to displace southward along the southern jet stream accompanied by a rapid fall of temperature all over Japan in the same fashion as analysed by K. Suda (1955). Several cold air invasions accompanied by a progressive short wave in the westerlies cut off the warm air over the Okhotsk Sea and finally it developed into a blocking high of the split type during the period Sept. 3–7 as shown in Fig. 31. Other examples of consecutive development of ridges and troughs initiated by typhoon invasion in the Shūrin seasons of 1957 and 1952 are shown in Figs. 32 and 33. They all show quite similar stages in the formation of a blocking flow pattern in East Asia.

Namely;

Stage 1: A typhoon invades into westerlies trough near Kyūshū. Summer flow type prevails with hot weather in Japan.

Stage 2: Ridges over Kamchatka and the Okhotsk Sea are developing through a supply of warm air transported by a typhoon.

Stage 3: In the east side of Kamchatka, northwest wind blows stronger with developing a ridge over the Okhotsk Sea. And then, the first surge of cold air takes place over the Bering Sea, which causes a trough to develop. This corresponds the first southward shift of the westerlies along 180° (see Fig. 28).
Fig. 32. Same as Fig. 30 but for Shūrin in 1951.

Fig. 33. Same as Fig. 30 but for Shūrin in 1957.
Stage 4: The development of a trough over the Bering Sea brings cold air to the south and warm air to the north. The latter (warm air) advection builds up a ridge over the west coast of North America. And a cold air advection on both sides of the Okhotsk Sea seclude a ridge into a blocking high. By these consecutive developments of the upper flow pattern, warm air (positive height anomaly) progresses to the north and cold air (negative height anomaly) to the south as shown in Fig. 25.

At the same time, the cold air around the pole surges to the south over the Bering Sea. With the developing and advancing to the north of the Okhotsk ridge, the cold air over northeast Siberia surges to West Japan, which is followed by the third surge of cold air over the Ural mountains. These phenomena illustrate the westward progress of the southward shift of the westerlies (see Fig. 28).

1.4 Peculiarity of the upper-air pattern from the viewpoint of energy consideration

To analyse the alternate increase in amplitude of troughs and ridges, the historical series of 5-day mean 500 mb charts reproduced in Fig. 30 were studied again from the viewpoint of energy dispersion. There appeared a rapid eastward progress of the developing westerlies waves. These increases in amplitude appeared to travel faster than either the wave or the zonal westerlies, indicating at least superficial agreement with the group velocity.

To examine this energy dispersion more closely, the isopleth of the north-south wind component expressed in terms of height difference for each 10° longitude along 50°N latitude circle in 1951 is shown Fig. 34a. The height differences were calculated on 5-day mean anomaly charts mainly to exclude the possibility of the normal circulation masking some of the perturbations. This time-longitude chart is constructed for the period Aug. 9–13. to Sep. 18–22. at 50°N. The positive figures represent the south wind component and the negative ones the north wind component.

In the isopleth the flow of energy is shown by a solid line connecting centers of

![Fig 34a. Time-longitude isopleth of the 5-day mean geostrophic meridional wind along 50°N latitude circle for 1951.](image-url)
maximum meridional flow. On Aug. 19–23, near 140°E, the maximum of southerly flow developed in association with the sudden buildup of a trough by the typhoon at about 120°E. This was followed on Aug. 24–28 by the maximum of northerly flow at about 165°E. Then the southerly flow at about 165°W attained its maximum value and this progressive increase in meridional flow continued with a northerly maximum at about 120°W on Aug. 29–Sep. 2, until it could not be traced clearly further eastward.

It should be emphasized here that the progression of energy cannot be traced back to its origin to the west of 120°E, whence the energy progressed to the east increasing the amplitude of the westerly wave. As another example, typhoon No. 10 in 1957 is shown in Fig. 34b. Typhoon No. 10 attacked West Kyūshū on the 6th Sept., 1957. From then, a new energy of wave propagates eastward in the same fashion as in the typhoon Marge (1951).

The velocity of this progress, the group velocity, was computed on the isopleth of 5-day mean meridional flow in the same way as done by A. V. Carlin (1953) and the result was compared with the calculated group velocity using the equation derived by C. G. Rossby (1949).

Table 7. Comparison of computed $C_g$ with observed $C_g$.

<table>
<thead>
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<th>Period</th>
<th>$U$</th>
<th>Computed $C_g$</th>
<th>Observed $C_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 19–23</td>
<td>9.4 m/sec</td>
<td>15.2 m/sec.</td>
<td>17.2 m/sec.</td>
</tr>
<tr>
<td>Aug. 24–28</td>
<td>7.0</td>
<td>11.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Aug. 29–Sep. 2</td>
<td>6.7</td>
<td>10.0</td>
<td>12.2</td>
</tr>
</tbody>
</table>

* $C_g = \frac{Uk^4 + (3Uq^2 + \beta)k^2 - \beta q^2}{(k^2 + q^2)^{3/2}}$

where $q^2 = f^2/2D_h$, $k^2 = 4\pi^2/L^2$. $C_g$: group velocity, $f$: Coriolis parameter, $\lambda$: dimension of wave length, $D_h$: height of the homogeneous atmosphere, $L$: wave length.
Calculation of the group velocity $C_v$ using the equation was based on 5-day mean 500 mb chart, and the zonal current of the westerly flow was computed over the half hemisphere (60°N to 40°N) centered on the longitude at 180°.

The quantitative agreement between calculated and observed values of the group velocity is seen in Table 7, resulting in the conclusion that the energy propagated downstream with the group velocity $C_v$ rather than the general current $U$.

In sum, the present study on the seasonal change in the flow pattern from summer to Shūrin establishes the following facts:

1. The weather in the Shūrin season in Japan is closely connected with the worldwide flow pattern as well as with the regional circulation aloft.

2. The typhoon which appears in late summer does a trigger action for the starting of disturbances in the westerlies.

3. New trough formation, which may be ascribed to typhoon invasion in the westerlies, seems to affect the westerly wave, say, increasing amplitude is transferred downstream in the consecutive manner with a speed nearly equal to the calculated group velocity based on Rossby’s formula.

4. With an increase in amplitude of the trough and ridge in the westerlies, cold air bursts equatorward and warm air poleward bringing cold Shūrin to Japan and warm weather over the North Pole. The blocking flow pattern is formed by these synoptic processes.

5. The great positive height anomaly around the pole breaks into three branches, resulting in the decrease of westerly wave number from four (summer) to three (Shūrin) corresponding to the seasonal weather change in Japan.

6. Three strong ridges are formed in the westerlies by these three positive height anomalies persisting through the Shūrin season.

2. On the formation of the meridional air flow pattern associated with a large-scale cold air outbreak in Japan

The cold air outbreak in East Asia is one of the striking phenomena of the winter monsoon. Many studies on the northwest monsoon such as by K. SUDA (1955), and A. KURASHIMA (1959) were mainly directed to the regional circulation in East Asia.

However, the cold air outbreak is observed not only in East Asia but also in Europe and North America. From a hemispheric point of view, the cold air outbreak is considered as a seasonal phenomenon accompanied by large-scale meridional heat exchange. (H. WADA, 1965)

2.1 Characteristics of the northern hemispheric upper-air flow pattern associated with a persisting cold air outbreak in Japan

The heating and cooling rate of the atmosphere calculated by the dynamical method is shown in Fig. 35, which shows that the air is cooled north of 50°N and heated south of 50°N (T. ASAKURA and A. KATAYAMA, 1964). Accordingly, the meri-
bution of normal heating and cooling rate in January and July estimated by a dynamical method.

dional temperature gradient becomes increasingly large if the air motion is only in the zonal direction. But the atmosphere itself has a tendency to make uniform the air temperature distribution. In other words, there occurs a meridional motion accompanied by a cold air outbreak.

In the present paper, the flow patterns associated with a cold air outbreak lasting at least more than fifteen days are analysed by northern hemisphere 500 mb composite maps for five cases. As is indicated in Fig. 36, 5-day mean temperatures in Japan are persistently higher than normal before the cold air outbreak and drop suddenly below normal when the cold air breaks out. Next, the upper-air flow pattern associated with persisting cold weather is compared with that of persisting warm weather. The 500 mb composite map for cold weather in Japan is shown in Fig. 37, in which is found a drastic pattern with warmer temperature than normal in the northern latitudes and colder temperature than normal in the southern latitudes. The axis of the strong westerlies displaces to the south of Japan. This flow type is classified as Z_2 in Part I. The strong ridge over the Taimyr Peninsula corresponds

Fig. 35. Zonal mean profile of normal heating and cooling rate in January and July estimated by a dynamical method.

Fig. 36. Variations of 5-day mean temperature anomaly in Japan before and after the cold air outburst.

Fig. 37. Northern hemisphere 500 mb composite map for cold weather persisting more than fifteen days in Japan.
to the strong Siberian high at the ground surface, the strong trough near Japan corresponds to the development of the Aleutian low.

It is interesting to note that the same type of flow pattern as in East Asia is observed simultaneously in the east of North America, England and Central Europe. This seems to suggest that the large-scale cold air outbreak in East Asia should not be considered as a regional one but part of a hemispheric phenomenon. Here, we are reminded of the severe cold winter that visited Japan (called Unusual Heavy Snow Fall in the Hokuriku district) in Japan of 1963, concurrently with the abnormal cold waves that attacked not only West Europe but also the east of North America, and brought a lot of disasters. On the other hand, people living in such higher latitudes as Kamchatka, Alaska, North Canada and Greenland enjoyed in that season an abnormal warm winter. These districts are just the ridge regions with the positive height anomaly of 500 mb, as shown in Fig. 37. In short, when the cold air bursts out toward Japan on a large scale, the polar region is covered by a warmer air-mass than normal and the middle latitude zone is covered by a colder air-mass.

![Fig. 38. Same as Fig. 37 but for warmer winter in Japan.](image)

On the other hand, the composite map of five cases of more than 15 consecutive warm days shows a striking reversed upper-air flow pattern as compared with the cold one shown in Fig. 38. That is, during warmer weather in Japan the polar region is covered by an air-mass colder than normal and the middle latitude zone by a warmer air-mass. The polar vortex shrinks and the subtropical high belt develops, resulting in a strong zonal westerly with less meridional exchange of air, and then cold air is accumulated in the polar region and warm air in middle latitudes.

### 2.2 Synoptic process of the formation of the meridional flow pattern causing a large-scale outburst of cold air

The synoptic process from the stage of warmer winter to that of colder winter in Japan is analysed from the viewpoint of hemispheric flow.

1) *Variations of the zonal index and zonal mean 500 mb height*

In the warmer winter stage, the zonal wind speed averaged along the 50°N
latitude circle is stronger than normal (about 14 m/s) but begins to slow down before the fifteen-day when the cold air outbursts and becomes weak (about 11 m/sec) in the colder winter stage, as shown in Fig. 39. This peculiar change is observed more strikingly in East Asia. And the cold-air bursts out in the course of changing the flow pattern from the high index to the low index stage.

The polar air mass also shows a variation as indicated in Fig. 40, with the 500 mb height anomaly corresponding to the mean temperature anomaly between 1000-500 mb. As mentioned above, the colder air mass than normal is accumulated in the polar region to the north of 50°N during the warmer winter stage. After that, the center of cold air mass displaces to the south as shown in Fig. 40 and reaches 50°N within fifteen days, and 40°N within ten days of cold air outbreaks into Japan.

On the other hand, the warm air mass moves from middle latitudes to the north and finally reaches the polar region, when cold air outbreaks come over to Japan. Namely, with an increase of meandering of the upper westerly flow, corresponding to a weak zonal air-flow, the colder air mass is steered to the south and the warmer air mass to the north, resulting in a large-scale meridional heat exchange.

2) Development of a ridge over England and the cold air outbreak in East Asia

The development of westerly waves from the warmer winter stage to the colder winter stage is analysed by using the series of 5-day mean 500 mb composite maps, and arranged in the following four stages:

Stage 1: This stage is associated with warmer weather in Japan. The amplitudes of westerly waves are small and the zonal westerly flow is predominant in middle latitudes (Fig. 38). The polar vortex accompanied by the polar air mass shrinks around the pole.

Stage 2: As shown in Figs. 39 and 40, the development of westerly flow begins fifteen days before the cold-air outbursts. The most striking variation of westerlies is the remarkable rising of 500 mb height near England, resulting in the formation of a ridge over the Atlantic Ocean. The development of this ridge forms a favorable flow pattern to the outburst of the polar air mass into Europe. Then, 500 mb height falls in Europe, while the zonal flow still persists in East Asia with warmer weather in Japan (Fig. 41a).
Stage 3: As shown in Fig. 41b, the positive height anomaly near England retrogrades to the northwest with its development. This ridge starts from the Mediterranean Sea (twenty-five days before the onset of cold-air outburst in Japan), then advances near England (fifteen days before the same) and Greenland (five days before the same). The retrogression of the ridge in the westerlies is one of the blocking phenomena associated with the development of the ridge in the west coast of North America. In consequence of the development of waves, the polar air begins to invade North America and at the same time bursts over Europe, resulting in an intensification of the trough in Europe. This modification of upper westerlies is transferred downstream and forms a ridge over Central Asia and North Siberia. This flow pattern is favorable for the development of the Siberian anticyclone.

Furthermore, the positive height anomaly begins to invade the polar region and the negative height anomaly begins to shift southward as shown in Fig. 40. In other words, a large-scale exchange is taking place in this stage.

Stage 4: The cold air streams out to the south on a large scale in this stage. As shown in Fig. 37, the amplitudes of westerly waves increase and the meridional flow is predominant. Particularly, the ridge on the Siberian Continent develops, bringing cold-air outbursts to Japan.

Summarizing the above results, the ridge over the Mediterranean Sea advances to the northwest over the Atlantic Ocean with its development and then the westerlies begin to meander. After the ridge reached Greenland, two phases develop in the westerlies. One is the new formation of a trough over Europe and a ridge over the Siberian Continent, and the other is the reinforcement of the ridge over the west coast of North America. Between these two ridges, there develops a trough directly over Japan. The polar air penetrates into this trough, causing the northwest monsoon in East Asia.

2.3 Statistical evidence of the role of the ridge over the Atlantic Ocean

It seems probable that the ridge near England plays an important role in the
development of westerlies from zonal to meridional flow type. To examine it statistically, the correlation maps between the 500 mb height near England and that over the northern hemisphere are calculated by using the ten-day means of 500 mb height anomaly for winters in 1959–1961. Fig. 42a is the simultaneous correlation map which shows that a ridge develops near England and a trough is formed over Europe. The cold air bursts out over Europe while Japan is covered with warm air. Comparing Fig. 42a with Fig. 41a, one can easily find close resemblance in their characteristic distributions. This corresponds to stage 2.

The correlation map of ten days later (Fig. 42b) shows the ridge has moved to Greenland and that at the same time a ridge has been newly formed over Siberia, below the normal height over Japan and the Central Pacific. Furthermore, the positive height anomaly covers the polar region. These characters are quite similar to those of the 500 mb composite map for the cold-air outbreak as shown in Fig. 37, corresponding to the stage 3 or 4.

Based on these facts, we may conclude that the ridge near England plays an important role in the evolution of the upper westerly from the zonal to meridional flow type.

2.4 Physical climatology on the formation of the meridional flow pattern

A large-scale cold-air outbreak is considered the variation from the zonal flow type to the meridional flow type on a hemispheric scale. This is also reflected on the variations of kinetic energy and the amplitudes of westerly waves.

The kinetic energy of zonal motion over the areas between 30°N and 70°N for each stage was calculated by an electronic high-speed computer on the basis of the equation of geostrophic wind and the result is tabulated in Table 8. (T. Arasuka (1965)).
As shown in Table 8, high energy in stages 1-2 (warmer winter in Japan) changes into low energy in stage 4 (colder winter in Japan). The decreasing of energy appears at stage 3, when the meridional heat exchange begins.

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_x$</td>
<td>97.71</td>
<td>96.34</td>
<td>80.96</td>
<td>73.24</td>
</tr>
</tbody>
</table>

Table 8. Kinetic energy of zonal motion ($K_x$) for each stage.

$10^{24}$ erg/sec.

![Graphs showing wave number and latitude for stages 1, 3, and 4.](image)

Fig. 43. Spectrum of harmonic waves of westerlies in higher latitudes for each stage.
Spectral analysis of westerly waves in higher latitudes shows the predominance of wave number 2 at stage 1 as shown in Fig. 43. But at stage 4 of cold-air outburst, wave number 2 decays and wave numbers 1 and 3 are predominant. This is caused by the interaction among the westerly waves (B. Saltzman, 1962). The magnitude of the interaction is calculated by using an electronic computer by the method used by T. Murakami (1965), and tabulated in Table 9.

<table>
<thead>
<tr>
<th>Wave Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stages 1–2</td>
<td>-10.2</td>
<td>-55.5</td>
<td>-38.5</td>
<td>-23.1</td>
<td>-10.2</td>
<td>31.8</td>
</tr>
<tr>
<td>Stage 3</td>
<td>4.3</td>
<td>-6.0</td>
<td>-9.1</td>
<td>-2.6</td>
<td>-1.7</td>
<td>-18.9</td>
</tr>
<tr>
<td>Stage 4</td>
<td>4.5</td>
<td>-32.5</td>
<td>13.7</td>
<td>-10.6</td>
<td>-24.0</td>
<td>-9.2</td>
</tr>
</tbody>
</table>

Negative signs in Table 9 mean supplies to, and positive signs those from, other waves. At stages 1–2, the long waves add energy to the short waves. The largest source of energy supply is wave number 2. In stage 3, wave number 1 is given energy, which is different from what takes place in stage 1. At stage 4, wave numbers 1 and 3 are given energy while wave number 2 still adds energy to other waves.

In sum, through stages 1–4, wave number 2 is the largest energy source. The next question is the energy source of wave number 2 itself. Considering a barotropic process, the energy supply supply from zonal motion to other waves were calculated by an electronic high-speed computer and the result is tabulated in Table 10. (T. Asakura (1965)).

<table>
<thead>
<tr>
<th>Wave Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stages 1–2</td>
<td>-26.4</td>
<td>39.5</td>
<td>-112.1</td>
<td>-52.4</td>
<td>-11.6</td>
<td>-25.1</td>
</tr>
<tr>
<td>Stage 3</td>
<td>-5.3</td>
<td>42.3</td>
<td>-75.9</td>
<td>-29.3</td>
<td>-9.9</td>
<td>-41.5</td>
</tr>
<tr>
<td>Stage 4</td>
<td>-3.5</td>
<td>15.3</td>
<td>-60.6</td>
<td>-8.4</td>
<td>12.2</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Special attention must be paid to the fact that wave number 2 is always positive while the others are mostly negative. That is, energy is supplied to wave number 2 from zonal motion and then wave number 2 exports energy to other waves. In other words, wave number 2 consumes the energy of zonal motion bringing up other waves. And the energy of zonal motion is thought to be supplied by the available potential energy (F. A. Krueger and J. S. Winston (1965)). In short,

1. A large scale cold-air outbreak in Japan is associated with a large-scale meridional heat exchange and Z flow type.
2. A large-scale flow pattern with cold-air outbreaks in East Asia goes with a
similar outburst flow pattern in Central Europe and the east coast of North America at the same time.

(3) The development of the upper flow pattern from stage 1 to 4 is initiated by the growth of the ridge over the Atlantic Ocean.

(4) This ridge retrogrades to the northwest near Greenland and blocks the upper air westerlies. In consequence of this movement, the trough over Europe and the ridges over Siberia and the west coast of North America become strong, resulting in the polar air-mass outbursts to East Asia, Central Europe and the east of North America.

(5) The variations of westerly waves are caused by the energy supply from zonal motion to wave number 2, which gives its energy to other waves. Consequently, wave number 2 decays and wave numbers 1 and 3 develop, resulting in a cold air outburst at stage 4.

Part III

On the formation of the upper-air flow pattern in Baiu and cool summer related to the circulation and heat source near the Tibetan Plateau

1. Statistical relations between the upper-air circulation near India and the one in East Asia during summer

The period from the beginning of June to the middle of July is characterized by prolonged bad weather with overcast skies and intermittent rain, and is known as the Baiu season in Japan and Mai-yü in China. Owing to its climatological and agricultural importance this phenomenon has been treated in many studies and various theories have been proposed for its explanation.

In his pioneer work at the end of last century, A. WOEIKOF (1860) explained Baiu by the change of monsoon winds from the winter north-westerlies to the summer southeasterlies. At the beginning of this century, T. OKADA (1910) emphasized the importance of the anticyclone over the Sea of Okhotsk. This theory was supplemented by many authors based on the concept of air-mass.

After World War II, M. OKUTA (1950) confirmed that the Okhotsk high was of the warm type extending to a high level. T. MURAKAMI (1951) made an analytic study of the Baiu season and found that it sets in with the formation of the branch of the subtropical westerly jet stream over Japan and ends with the disappearance of its southern branch. Many other studies on Baiu were reviewed by K. TAKAHASHI and the present writer (1955), written in Japanese and then translated into Chinese. Recently, M. IMADA (1963) studied Baiu circulation by using 100 mb charts and M. YOSHINO divided the upper-air circulation in this season into four stages. H. FLOHN (1957) and T. MURAKAMI (1958) stressed the importance of the heat source near the Tibetan Plateau, and a simulated climatology of the general circulation with the hydrodynamic equation was made by S. MANABE and J. SMAGORINSKY (1965).

In the present study, Baiu is studied as a seasonal peculiarity of the general
circulation of the atmosphere rather than a local weather condition and a close connection is found between the upper-air circulation in the neighbourhood of the Tibetan Plateau and that over East Asia. It is also established that a heat source in the neighbourhood of the Tibetan Plateau as well as a cold source in the northeast of Japan plays an important role in forming a blocking flow pattern in East Asia.

1.1 Relationship between the southwest monsoon in India and Baiu in East Asia

The blocking flow pattern in early summer is a characteristic flow in the Baiu season. As shown in Fig. 44, which is a typical example of flow at 500 mb level for pronounced Baiu weather (5-9 June 1964), the upper westerlies have two branches, the one flowing to the north of Japan with an anticyclonic curvature and the other over south Japan with a cyclonic curvature. In other words, there appears an anticyclone near the Okhotsk Sea and a trough over West Japan, and SW wind flows along Japan proper. Under this southwest wind, a front called Baiu Zensen remains stationary and cyclones move subsequently along this front, which brings about a rainy season in Japan. This blocking flow pattern is associated with Mai-yü in China as pointed out by M. T. TANG (1957) and C. W. CHEN (1964).

1) Onset of Baiu in Japan and the SW monsoon in India

First among the synoptic studies on the onset of the monsoon, M. T. YIN (1949) pointed out that the SW monsoon sets in when the westerly axis moves to the northern side of the Tibetan Plateau from the southern side.

The seasonal shift of the axis of the westerlies seems to be correlated closely to the seasonal march of weather in Japan. To make clear its variation in the season just preceding Baiu in 1954, the axis of the westerlies for the three 5-day periods for May 16-20 and 26-30 are shown in Fig. 45. As is shown in this figure, in the first period (May 16-20, 1954) when the Okhotsk Sea high is not formed, the axis of the westerlies runs south of the Tibetan Plateau and passes over North Japan with a slight anticyclonic curvature. And finally in the last period (May 26-30, 1954), it skips over the Tibetan Plateau and runs to the north of it, whereas near Japan it moves definitely to the south and extends from west to east along its southern coasts. It is interesting to note that this last period coincides well with the data of the SW
monsoon onset as reported by the India Meteorological Office on the one hand and with the data of temperature drop in Japan on the other. So it seems highly probable that both phenomena, although taking place thousands of miles apart, are closely linked with the seasonal variation of the westerly flow. The above interconnection of westerlies in early summer was first pointed out by the present writer (T. ASAKURA (1955)), and was later discussed by T. MURAKAMI (1955) in connection with Baiu and by S. Y. Dao (1958) with reference to Mai-yü in China.

This point of view is also supported by statistical studies. The dates of their first appearance as determined by Y. SUGIMOTO (1951) for Baiu and L. A. RAMDAS (1954) for the SW monsoon were compared with each other for the period of 1930-1950. The result is shown in Fig. 46, where black and white circles indicate the beginning of Baiu at Tōkyō and the SW monsoon at Travancore-Cochine, respectively. As will be readily seen in this figure, the parallelism of the two curves is indisputable and a late or early monsoon seems to be followed by a late or early Baiu season, respectively.

2) Simultaneous relation between a high over the Okhotsk Sea and a monsoon low in India

The significant fact to be noted in the Baiu season is a marked pressure rise over the Okhotsk Sea and a considerable pressure fall over the sea off the south coasts of Japan and over India. T. MURAKAMI (1959) found that the moisture flow in an early
stage of the Baiu season is controlled by the upper-air westerlies from India. To make clear statistically the relationship between SW monsoon in India and Baiu flow in East Asia, correlation coefficients were calculated. 5-day mean surface pressures at (60°N, 150°E; 50°N, 150°E), (30°N, 130°E; 30°N, 120°E) and (30°N, 80°E; 20°N, 70°E) are chosen for the Okhotsk Sea high, the low pressure in south Kyūshū and the Indian low pressure, respectively. The correlation coefficients at each pair selected above were computed for May 21—June 19 for 5 years by using the 5-day mean pressure anomalies.

The correlation coefficients between them are:

Indian low...............Okhotsk Sea high —0.56
Indian low...............low pressure in south Kyūshū 0.45

This means that when the Indian low, an index of monsoon activity, develops both the Okhotsk Sea high and the low in south Kyūshū are intensified simultaneously. That is, an active monsoon in India is correlated with an active Baiu in Japan. And this seems to support H. Flohn’s analysis (1957) that monsoon rains in East Asia have a close interconnection.

1.2 Cool summer in north Japan and the circulation over the Tibetan Plateau

The three summers of 1964–1966 were remarkable for their coolness in North Japan, while the western portion of the country suffered from hot summer all the while. A low temperature distribution in North Japan with high temperature in West Japan is liable to cause bad harvest, typical examples being the years 1934 and 1964 as shown in Fig. 47.

To elucidate the upper-air flow patterns bringing forth such a contrasting temperature distribution, the 500 mb composite maps for a cool summer in North Japan with a hot summer in West Japan (Fig. 48a) and for a hot summer in North Japan with a cool summer in West Japan (Fig. 48b), are constructed using the monthly

Fig. 47. Temperature anomaly distribution for a cool summer in North and a hot summer in West Japan in July of 1964 and 1934.

Fig. 48a. The composite map of monthly mean 500 mb height anomaly for a cool summer in North Japan with a hot summer in West Japan.
mean 500 mb maps in July. As shown in Figs. 48a and 48b, quite different air-flow patterns are formed in East Asia corresponding to the temperature distribution in Japan. Their features are summarized as follows:

<table>
<thead>
<tr>
<th>Cool Summer in North Japan with Hot Summer in West Japan</th>
<th>Hot Summer in North Japan with Cool Summer in West Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) North Japan is covered with a negative height anomaly and NW wind flows from Northeast Siberia.</td>
<td>(i) North Japan is covered with a positive height anomaly and a nearly zonal wind flow.</td>
</tr>
<tr>
<td>(ii) West Japan is covered with a positive height anomaly which extends from the Tibetan Plateau.</td>
<td>(ii) West Japan is covered with a negative height anomaly extending from Southeast Asia.</td>
</tr>
<tr>
<td>(iii) A trough stagnates off the east coast of Hokkaidō.</td>
<td>(iii) A trough stagnates over the Bering Sea and a ridge over Hokkaidō.</td>
</tr>
</tbody>
</table>

To analyse more closely the difference between them, the differential map between them is calculated. As is shown in Fig. 48c, North Japan is covered with a large negative height anomaly and a strong ridge stagnates over North Siberia. Such a flow pattern is favorable for advecting the cold air-mass to North Japan. Special attention must be paid to the fact that the large positive height anomaly stagnates over the Tibetan Plateau, part of it extending to the east and covering West Japan.

To study statistically the role of the Tibetan anticyclone in the upper-air circulation in East Asia, the correlation map between them is calculated using the monthly mean 500 mb height in July for 1946-1965 (Fig. 49). A surprisingly similar pattern is found between the correlation map (Fig. 49) and the composite map (Fig. 48c).

That is, when the anticyclone over the Tibetan Plateau develops:

(i) The anticyclone covers China and West Japan entailing a hot summer in West Japan.
(ii) A trough is formed from Northeast Siberia to the east coast of Japan, resulting in a cool summer in North Japan.
(iii) A trough is formed from the North Polar Sea to Kamchatka.
(iv) The Pacific anticyclone is weak and North Japan is confined in a cold-air pool.
The above results suggest that the Tibetan anticyclone is one of the factors in bringing about a cool summer in North Japan and a hot summer in West Japan. Recently, M. Yoshino (1967) found a significant correlation (−0.81) between the circulation at the 100 mb level in South Asia and East Asia. Thus, the upper-air circulation between South Asia and East Asia is known to have a close interrelation.

Furthermore, to make clear the effect of the Tibetan anticyclone, we chose four examples of stronger and weaker Tibetan highs in May, and prepared the composite maps for the following June and July.

Fig. 49. Simultaneous correlation map between the Tibetan high and 500 mb heights over the northern hemisphere in July of 1946–1965.

The above results suggest that the Tibetan anticyclone is one of the factors in bringing about a cool summer in North Japan and a hot summer in West Japan. Recently, M. Yoshino (1967) found a significant correlation (−0.81) between the circulation at the 100 mb level in South Asia and East Asia. Thus, the upper-air circulation between South Asia and East Asia is known to have a close interrelation.

Furthermore, to make clear the effect of the Tibetan anticyclone, we chose four examples of stronger and weaker Tibetan highs in May, and prepared the composite maps for the following June and July.

Fig. 50a. Composite maps of 500 mb height anomaly in June and July when the Tibetan high develops in May.
As shown in Fig. 50a, when the Tibetan anticyclone is stronger than normal in May, the following flow patterns in June and July show a typical Baiu flow type in East Asia. On the other hand, when the Tibetan anticyclone is weaker than normal in May, the following flow patterns in June and July show a typical hot summer type. These striking results suggest that the Tibetan anticyclone plays an important role in forming a flow pattern in East Asia in the Baiu season.

Fig. 50b. Same as Fig. 50a but for a weak Tibetan high in May.

As shown in Fig. 50a, when the Tibetan anticyclone is stronger than normal in May, the following flow patterns in June and July show a typical Baiu flow type in East Asia. On the other hand, when the Tibetan anticyclone is weaker than normal in May, the following flow patterns in June and July show a typical hot summer type. These striking results suggest that the Tibetan anticyclone plays an important role in forming a flow pattern in East Asia in the Baiu season.

Fig. 51a. One month lag correlation map between Tibetan high in May and 500 mb heights over the northern hemisphere in June.
Fig. 51b. Same as Fig. 51a but between June and July.

Fig. 51c. Same as Fig. 51a but between July and August.
To examine statistically the after-effects of the Tibetan anticyclone on the flow pattern over East Asia, one month lag correlation between Tibetan anticyclone and the 500 mb height is calculated using the data for 1946-1965.

The correlation coefficients are not so large as expected, nearly the same features of the upper-air flow pattern as on the composite map (Fig. 50) are reproduced on the correlation map (Fig. 51a).

When the Tibetan anticyclone is stronger than normal in May, the following patterns prevail in June (Fig. 51a):

(i) The ridge over the Okhotsk and Bering Sea is strong and the Pacific anticyclone is weak.
(ii) The blocking flow pattern is formed over Japan, resulting in typical Baiu weather in Japan.

When the Tibetan anticyclone is stronger than normal in June, the following patterns prevail in July (Fig. 51b):

(i) West Japan is covered by the Tibetan anticyclone, resulting in a hot summer in West Japan, while East and North Japan are still under the effect of the blocking flow pattern of Baiu weather.
(ii) A ridge is formed in the north of the Okhotsk Sea and the Pacific anticyclone is weak. North Japan is covered with cold air.

When the Tibetan anticyclone is stronger than normal in July, the following patterns prevail in August (Fig. 51c):

(i) The Pacific anticyclone is weak.
(ii) The Tibetan anticyclone extends to the north and forms a ridge over Lake Baikal, whence northwest wind flows to North Japan, resulting in a cool summer there.

Summarizing the above results, we may conclude that the Tibetan anticyclone at the 500 mb level plays an important role in forming the particular flow patterns in East Asia bringing a cool summer in North Japan and a hot summer in West Japan.

2. On the numerical experiment to study the role of the heat source near the Tibetan Plateau and of the cold source near the Okhotsk Sea

As stated before, the subtropical jet stream is displaced suddenly to the north of the Tibetan Plateau at the last week of May when the SW monsoon bursts over India (M. T. Yin 1949). P. Koteswaram (1958) found that the Indian monsoon occurs together with the establishment of a subtropical high over Tibet, in the south of which a marked easterly jet stream overlies. H. Flohn (1957) pointed out that the northward displacement of the jet stream in India is connected with the contemporary increase of air temperature over the Tibetan Plateau. T. Murakami (1958) showed that the warmer Tibetan anticyclone is formed by the heat source over the Tibetan Plateau and that at the same time the jet stream is displaced to the north of the Tibetan Plateau. Recently, H. Flohn (1964) studied the easterly jet stream whose energy is derived from the energy conversion of available potential energy to kinetic energy over China. In order words, there occurs an upward motion over China, the cause of which is perhaps the forced upgliding of the easterly wind by
the Tibetan Plateau. Y. Mintz and A. Arakawa (1964) proved by their numerical experiments that the Siberian anticyclone can not be formed only by radiative cooling and sensible heat exchange. They also pointed out that the Tibetan Plateau obstructs the heat exchange between warm air over the Indian Ocean and cold air over the Siberian Continent, resulting in a formation of the Siberian anticyclone. From all these, the existence of the Tibetan Plateau is found to influence the climate in East Asia widely and profoundly.

Furthermore, the Tibetan Plateau receives intensive short wave radiation and transfers the sensible heat to the atmosphere, and a vast amount of precipitation due to the SW monsoon releases much condensation heat to the atmosphere, and then a large heat source is formed over India.

2.1 Normal heat distribution in June

It is easily understood that in early summer the vast and elevated Tibetan Plateau acts as a heat source. The staff members of the Academia Sinica, Peking (1958) estimated the mean amount of direct heating from the ground surface of the Tibetan Plateau, considering radiative cooling, condensation heating and temperature advection. T. Murakami (1958) also estimated the heating rate over the Tibetan Plateau using H. Flohn’s analysis of upper-air temperature.

On the other hand, there flows a cold current over the northeast Pacific Ocean which cools the air mass above it. T. Okada (1910) stressed that this cold current is responsible for cool summer and prolonged Baiu weather in Japan.

The present winter (1964) studied the normal heat distribution in the northern hemisphere in January, April, July and October, based on the thermodynamic and vorticity equation, and discussed the climatological features of their distributions (T. Asakura, A. Katayama (1964)).
In the present paper, to study the effect of heat in early summer, the normal heat distribution in the layer between the 1000-mb and the 500-mb surface in June (Fig. 52) is obtained by the linear interpolation of a heat source in April and July calculated by the dynamical method.

As is seen in Fig. 52, a large heat source dominates over low latitudes with a center in the neighbourhood of India (about 150 Ly/day) and a cold source (about −90 Ly/day) is situated over the ocean to the south of Kamchatka where a cold current called Oyashio flows to the south.

These features of heat distribution were reproduced from the case study by T. Murakami (1957, 1958). East Asia lies just between the heat source over Southeast Asia and the cold source over the Pacific Ocean.

2.2 Simulation of the blocking flow pattern in the Baiu season by a numerical experiment

Many synoptic studies on the Baiu season pointed out two pronounced features of the upper-flow pattern in East Asia. The one is the monsoon trough near India accompanied by the Tibetan anticyclone in the upper troposphere and the other the blocking flow pattern in East Asia. However, the causes of these characteristic flow patterns have not yet been known. T. Murakami (1958) simulated the upper-tropospheric Tibetan anticyclone and stressed the importance of the heating effect by the elevated Tibetan Plateau. On the other hand, the cause of the blocking flow pattern in East Asia is ascribed to the cooling effect by the cold current near the Okhotsk Sea, though a quantitative physical explanation has not been tried.

The subjects to be studied are the reasons why the two rainy seasons in India and East Asia appear at nearly the same time in early summer and why the former is associated with the monsoon trough over India and the latter with the blocking high over the Okhotsk Sea.

1) Model equation

In the present paper, the characteristic upper-air flow pattern in India and East Asia is simulated based on the thermodynamic and vorticity equation considering the effect of the normal heat source near India and the normal cold source near the Okhotsk Sea. The calculations are carried out for 500 mb, 700 mb and 1000 mb levels in the northern hemisphere and geostrophic approximation is assumed. That is,

\[
\frac{\partial \zeta}{\partial t} = -u_x \frac{\partial (f+\xi_6)}{\partial x} - v_y \frac{\partial (f+\xi_6)}{\partial y} + f \left( \frac{\partial \omega}{\partial p} \right)_6
\]

(1)

\[
\frac{\partial \zeta_7}{\partial t} = -u_x \frac{\partial (f+\xi_7)}{\partial x} - v_y \frac{\partial (f+\xi_7)}{\partial y} + f \left( \frac{\partial \omega}{\partial p} \right)_7
\]

(2)

\[
\frac{\partial \zeta_{10}}{\partial t} = -u_x \frac{\partial (f+\xi_{10})}{\partial x} - v_y \frac{\partial (f+\xi_{10})}{\partial y} + f \left( \frac{\partial \omega}{\partial p} \right)_{10} + g \mathbf{K} \cdot \mathbf{F} \times \left( \frac{\partial \tau}{\partial p} \right)_{10}
\]

(3)

\[
\frac{\partial h_1}{\partial t} = -u_x \frac{\partial h_1}{\partial x} - v_y \frac{\partial h_1}{\partial y} + \frac{dp}{g} S_0 \omega_0 + Q_0
\]

(4)
where, $\zeta$: relative vorticity, $h_1$: thickness between 700 mb and 500 mb, $h_2$: thickness between 700 mb and 1000 mb, $v$: east-west wind component, $u$: north-south wind component, $Q_6$: heating or cooling rate between 700 mb and 500 mb, $Q_{8.5}$: heating or cooling rate between 700 mb and 1000 mb, $g$: acceleration of gravity, $f$: Coriolis' parameter, $\tau$: shearing stress, $\omega$: vertical $p$-velocity, $S$: stability, suffixes 5, 6, 7, 8.5, 10 mean 500 mb, 600 mb, 700 mb, 850 mb and 1000 mb respectively. Details of this calculation are presented in the Appendix.

The above equations are transformed into a finite difference form in order to be available for the electronic computer I.B.M. 7090 and the mesh size is 300 km, time interval 90 minutes and the domain of calculation is $23 \times 23$.

Fig. 53a. Normal 700 mb maps in may used as the initial map for this numerical experiment.

Fig. 53b. 700 mb pattern on the fourth day.

Fig. 53c. 700 mb pattern on the fifth day.

Fig. 53d. Same as Fig. 53c but for the eighth day.
2) Formation of the blocking flow pattern in East Asia

First, to make clear the heat effect, the flow patterns at 700 mb level are calculated by operating the heat source and sink in June on the normal pattern in May. As shown in Fig. 53e, the blocking flow pattern is formed over East Asia on the tenth day. The processes of the formation of the blocking high are traced back in the following way:

(i) The initial flow pattern is nearly zonal and a weak trough is formed over East Asia (Fig. 53a). Operating the heat to the initial flow pattern, a trough is formed by the heat source near India. By this newly formed trough near India, vorticity is transported downstream and a ridge over the inland of China and a trough near the coast of China are formed successively on the fourth day. But little change is found over middle and high latitudes where heating and cooling rate are weak. (Fig. 53b)

(ii) The trough near India remains stationary, resulting in the development of a ridge over the inland of China. As shown in Figs. 53c, d, this ridge develops stronger and stronger on the fifth and eighth days, and finally extends northward into the westerly flow over North Siberia deforming the westerly flow. The weak ridge near the Okhotsk Sea is formed by the cold source and stagnates there. The trough over the East China Sea also persists there with a tendency to develop. This upper-air trough corresponds to the Baiu front on the surface.

(iii) The ridge over North Siberia is steered to the east by the upper westerly and reaches the north of the Okhotsk Sea and then stays there, an area of cold source and a favorable place for a ridge. On the other hand, the trough off the southern coast of Kyūshū remains stationary and develops. And so the upper westerly over East Asia bifurcates into two branches on the ninth day as shown in Fig. 54.

(iv) The ridge over Northeast Siberia lies stationary near the cold source of the Okhotsk Sea, while the trough near Kyūshū also develops. Finally a blocking high over the Okhotsk Sea and a low near Kyūshū are formed. This is a typical Baiu flow pattern as shown in Fig. 53e.
In India, in the meantime, some important changes occur in the upper-air flow pattern. That is, the trough near India and the ridge over the Tibetan Plateau are formed and remain stationary by the heat source over India. This is the typical upper-air flow pattern associated with the SW monsoon.

To sum up, the heat effects on the upper-air flow pattern are arranged in the following way:

The intensive heating centered near India plays a role to form a trough near India. By this newly formed trough, vorticity and warm-air are transported northward and a ridge is formed over the inland of China. Then a trough is formed over the East China Sea, and a flow of anticyclonic curvature is formed in the north of Japan associated with the cold source near the Okhotsk Sea. The stronger the trough fostered by the heat source near India, the stronger the ridge and trough downstream. And the ridge over the inland of China advances into the northern westerlies and finally forms a ridge there. This ridge is steered to the east by the westerly flow and stagnates near the Okhotsk Sea, a favorable place for it to develop because of a cold source. Then the blocking high is formed near the Okhotsk Sea. On the other hand, the two troughs near India and East China Sea develop in middle latitudes corresponding to the SW monsoon and Baiu weather in East Asia.

Thus, we may conclude that the climatological heat source and sink in June influence the upper-atmospheric circulation, resulting in the blocking flow pattern (typical Baiu flow pattern) in East Asia and the monsoon flow type in India at the same time.

2.3 The importance of the heat source over India for the formation of a blocking flow pattern in East Asia—Revaluation of Okada's Baiu theory

The theories on Baiu up to now have put stress upon the importance only of the cold source over the Okhotsk Sea (Okada, 1910). It is certain that the cold source near the Okhotsk Sea plays a role in the formation of a ridge there. But it is difficult
to explain the close relationship between Baiu in East Asia and SW monsoon in India only by the cold source near the Okhotsk Sea. Furthermore, it has not been ascertained whether a blocking flow pattern could be formed only by the cold source, that is without considering the heat source over India. One may also doubt whether the normal flow pattern in May itself can from a blocking flow pattern without the help of the heat source and sink.

To study more closely the effect of heat and cold sources on the upper-air flow pattern, a circular pattern is employed as the initial map, which is shown in Fig. 55a. The normal heat distribution in June is operated on this circular pattern, and we investigate the development of the westerly wave to form a Baiu flow pattern in East Asia and a monsoon flow in India.

Fig. 55a. Circular 700 mb map used as the initial map for the numerical experiment.

Fig. 55b. 700 mb pattern on the fourth day.

Fig. 55c. 700 mb pattern on the sixth day.

Fig. 55d. 700 mb pattern on the tenth day.
Numerical results are:

(i) The upper-air flow pattern in the higher latitudes shows little variation belonging to the nearly zonal flow type. On the third day, a monsoon trough is newly formed near India corresponding to the heat source, and a ridge near the Okhotsk Sea corresponding to the cold source. On the fourth day, troughs are formed near India as well as in South China, as shown in Fig. 55b.

(ii) On the sixth day, the monsoon trough and a Baiu trough are becoming strong and a ridge develops over China between the about two troughs and extends into the higher latitudes as shown in Fig. 55c. After that, part of this ridge is steered to the east by the westerly flow and amalgamated to a ridge over the Okhotsk Sea, resulting in the development of a ridge there.

(iii) On the tenth day, as shown in Fig. 55d, the upper-air westerly bifurcates into two branches and a blocking flow pattern is formed in East Asia with a trough near Kyūshū and a ridge over the Okhotsk Sea. In India, a monsoon trough is formed with a ridge over the Tibetan Plateau.

In such a way, nearly the same results as described in the previous section are obtained. This means that the normal heat and cold sources play a role in forming the characteristic upper-air flow pattern not only in East Asia but also in India.

Next, to make clear the heat effect on the upper-air flow pattern, the same calculation is carried out neglecting the heat source centering in India and considering only the cold source near the Okhotsk Sea. In other words, the numerical experiment for this case is the numerical revaluation of OKADA’s Baiu theory which insisted on the importance of the cold source near the Okhotsk Sea.

The results obtained are:

(i) The circular pattern indicates no changes, but a ridge is formed on the fifth day near the Okhotsk Sea corresponding to the cold source as shown in Fig. 56a, while no trough is formed over India as there is no heat source in this case.
On the eighth day, the ridge over the Okhotsk Sea decays and a very weak trough is formed in East Asia, as shown in Fig. 56b.

On the tenth day, nearly the same pattern with that of the eighth day is shown in Fig. 56c. Bifurcation of the westerly and a trough in India could not be formed. In other words, no Baiu flow pattern could be formed, there being no heat source near India.

It is interesting to note that the Baiu flow pattern cannot be formed solely by the cold source near the Okhotsk Sea. However, it is obvious that the ridge over the Okhotsk Sea is fostered by the cold source there and OKADA’S Baiu theory explains one of factors in the formation of the Okhotsk Sea high. That is, the effect of the cold source near the Okhotsk Sea on the upper-air flow is intensified by the addition from the heat source centered near India. Then OKADA’S Baiu theory must be revised by extending his idea to this latter source. It should be emphasized here that OKADA’S theory has been contradicted by the observational fact that the Okhotsk Sea high is a warm type formed dynamically, not by direct cooling. But the present simulation shows clearly the importance of atmospheric cooling as well as heating for the formation of the blocking flow pattern in East Asia.

**Conclusion**

The present paper studied:

(i) the relationship between the weather in Japan and the upper-air circulation in East Asia which is classified into six flow types (Part I),

(ii) the synoptic processes and causes of the formation of the blocking flow pattern in East Asia (Part II),

(iii) the causes of Baiu in East Asia relating to the atmospheric circulation and the heat source near the Tibetan Plateau (Part III).
In conclusion, the large-scale weather in Japan has a close relationship with the upper-air flow pattern. Especially, abnormal weather is often associated with the zonal flow type or blocking flow type in East Asia (Part I). The blocking flow type is associated with the characteristic features of Japan’s climate such as Shūrin and northwest monsoon. The Shūrin season begins with the formation of the blocking flow pattern which is initiated by a typhoon invasion into the westerly flow. The northwest monsoon becomes strong when the blocking flow pattern is formed in East Asia by a large-scale heat exchange between high and low latitudes (Part II). Another blocking flow pattern in early summer brings the Baiu season in East Asia. This blocking flow pattern is formed by the union of a large heat source near India and a cold source near the Okhotsk Sea. This is simulated by using an electronic high-speed computer (Part III).

The results are summarized as follows:

The upper-air circulations in East Asia are classified into six kinds of flow type basing on the temperature and precipitation in Japan. The high index zonal flow type brings forth higher temperature whereas the low index zonal flow type, wave flow type and blocking flow type are associated with lower temperature in Japan.

Precipitation in Japan is also controlled by the upper-air flow pattern but their relations are rather more complicated than in temperature. In general, the zonal westerly flow type, southwest flow type and meridional flow type bring on much rain, whereas the northwest flow type and anticyclonic flow type cause little rain in Japan.

It is emphasized here that the abnormal low temperature, much snow and heavy precipitation in Japan generally go with the blocking flow pattern in East Asia. Warmer winters in Japan are generally associated with warmer winters in Central Europe and colder winters in Central Siberia, and this is to be explained by the upper westerly wave trains.

The synoptic processes of the formation of a blocking flow pattern in the Shūrin season and winter seasons are next discussed:

The Shūrin falls within the season of typhoon visits to Japan and its neighbourhood. A typhoon generally decays after its invasion into the upper westerly flow giving deformation to it. The deformation of the westerly wave is, in turn, transferred to the east, and then the amplitudes of westerly waves are intensified, resulting in a formation of a large-scale meridional heat exchange and the splitting of the westerly flow into two branches. Finally, a blocking flow type is formed when the Shūrin season starts in Japan.

Another blocking flow pattern during winter is associated with a large-scale cold air outbreak in East Asia. This blocking flow pattern is caused by a large-scale heat exchange between high and low latitudes initiated by the development of a ridge over the Atlantic Ocean. With the development of this ridge, the polar air-mass streams out to Europe and North America and the ridges over the Asiatic Continent and the west coast of North America are strengthened. These two ridges progress to the north and finally amalgamate in the north of Japan. In this case, the upper-air flow in East Asia forms a blocking flow type resulting in persisting cold-air outbursts to Japan.
In early summer, Japan is visited by the Baiu season with a blocking flow pattern. The start of the Baiu season in East Asia coincides well with the displacement of the westerly flow from the south to the north side of the Tibetan Plateau when the SW monsoon starts in India. The monsoon low and the Okhotsk Sea anticyclone are linked with each other with a significant correlation.

Furthermore, the stronger the high over the Tibetan Plateau in early summer, the more predominant the blocking flow in East Asia. These close relations between the upper flow pattern in India and in East Asia are considered to be brought on by the atmospheric heat source near India and the cold source near the Okhotsk Sea. This is simulated by a numerical experiment by using an electronic high-speed computer.

The Baiu flow pattern East Asia and a monsoon trough are formed by the union of the heat source near India and the cold source near the Okhotsk Sea. The importance of the heat source near India should be emphasized here because the Baiu flow pattern could not be formed solely by the cold source near the Okhotsk Sea. Then, OKADA's Baiu theory should be revaluated by extending his idea to the heat source near India.

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Appendix

Vorticity equations and the thermodynamic equation which were presented in equations (1)–(5) are transformed into the following finite difference form:

\[ p^2 \left( \frac{\partial Z_2}{\partial t} \right) \cdot 2\Delta t = \bar{\eta} (A p^2 Z_2 + B, Z_2) + \frac{f^2}{m^2 g \Delta p} (\sigma_8 - \sigma_8) \] (6)

\[ p^2 \left( \frac{\partial Z_7}{\partial t} \right) \cdot 2\Delta t = \bar{\eta} (A p^2 Z_7 + B, Z_7) + \frac{f^2}{m^2 g \Delta p} (\sigma_8 - \sigma_8) \] (7)

\[ p^2 \left( \frac{\partial Z_{10}}{\partial t} \right) \cdot 2\Delta t = \bar{\eta} (A p^2 Z_{10} + B, Z_{10}) + \frac{f^2}{m^2 g \Delta p} (\sigma_{10} - \sigma_8) \] (8)

\[ \frac{\partial h_1}{\partial t} \cdot 2\Delta t = A \bar{\gamma} (Z_6, Z_7) + \frac{\Delta p}{g} S_6 \sigma_8 + \bar{\zeta}_6 - \frac{g k'}{\Delta p} \frac{\partial}{\partial \sigma} V_\xi | p^2 Z_6 | 2\Delta t \] (9)

\[ \frac{\partial h_2}{\partial t} \cdot 2\Delta t = A \bar{\gamma} (Z_7, Z_{10}) + \frac{\Delta p}{g} S_{6,5} \sigma_{6,5} + \bar{\zeta}_{6,5} \] (10)

where
Eq. (9) and eq. (10) are arranged in another form by using the notation

\[ \left( \frac{\partial Z}{\partial t} \right)_i \cdot 2Dt = \tau_i \]

That is:

\[ \tau_5 - \tau_7 = A\mathcal{J} (Z_5, Z_7) + \frac{dp}{g} S_6 \sigma_6 + \tilde{Q}_6 \]  

\[ \tau_7 - \tau_{10} = A\mathcal{J} (Z_7, Z_{10}) + \frac{dp}{g} S_9 \sigma_9 + \tilde{Q}_{9,5} \]  

In a similar way, for the layers of 300 mb and 500 mb,

\[ \tau_5 - \tau_{10} = A\mathcal{J} (Z_5, Z_{10}) + \frac{dp}{g} S_4 \sigma_4 + \tilde{Q}_4 \]  

\( \sigma \)'s are determined by the above equations. That is:

\[ \sigma_4 = \frac{g}{S_4 dp} [\tau_5 - \tau_7 - A\mathcal{J} (Z_5, Z_7) - \tilde{Q}_4] \]  

\[ \sigma_6 = \frac{g}{S_6 dp} [\tau_5 - \tau_7 - A\mathcal{J} (Z_5, Z_7) - \tilde{Q}_6] \]  

\[ \sigma_{9,5} = \frac{g}{S_{9,5} dp} [\tau_7 - \tau_{10} - A\mathcal{J} (Z_7, Z_{10}) - \tilde{Q}_{9,5}] \]  

By inserting the above \( \sigma \)'s in equation (6)–(8), we get

\[ p^2 \tau_5 - \beta_5 \tau_5 = J_5 - \beta_6 J_6 - \beta_6 Q_6 - \frac{f^2}{g dpm^2} \sigma_4 \]  

\[ p^2 \tau_7 - \beta_7 \tau_7 - \beta_6 \tau_7 + \beta_6 \tau_5 + \beta_6 \tau_{10} = J_7 - \beta_9 J_8 - \beta_9 \tilde{Q}_{9,5} + \beta_6 J_6 + \beta_6 \tilde{Q}_6 \]  

\[ p^2 \tau_{10} - \beta_{10} \tau_{10} + \beta_6 \tau_{10} = J_{10} + \beta_6 J_6 + \beta_6 \tilde{Q}_{9,5} + \frac{f^2}{m^2 g} \frac{dp}{d\tau} \omega_{10} - \frac{g K}{dp} \tilde{V}_5 |p^2 Z_6| 2dt \]  

where

\[ J = \mathcal{J} (Ap^2 Z + B, Z) \quad J' = A\mathcal{J} (Z_{i+1}, Z_{i+1}) \]

Here, we assume that \( \tau_5 = 0, \sigma_{10} = 0 \) .................................................(20).

By inserting eq. (20) into eq. (17), we get;

\[ \Sigma \tau_5 = (4.0 + \beta_4 + \beta_6) \tau_5 + \beta_6 \tau_7 = F_5 \]

\[ \Sigma \tau_7 = (4.0 + \beta_9 + \beta_6) \tau_7 + \beta_6 \tau_5 + \beta_6 \tau_{10} = F_7 \]

\[ \Sigma \tau_{10} = (4.0 + \beta_6 + \beta_9) \tau_{10} + \beta_6 \tau_7 = F_{10} \]
where
\[ F = J_0 - \beta_0 J_0 + \beta_0 \bar{Q}_0 - \beta_0 \bar{Q}_0 = J_0 - \beta_0 (J_0 + \bar{Q}_0) + \beta_0 \bar{Q}_0 \]
\[ F = J_0 - \beta_0 J_0 + \beta_0 (J_0 + \bar{Q}_0) - \frac{\partial}{\partial p} k' \left| V_s \right| p^2 Z_{10} \cdot 2 \! dt \]
\[ S(p) = S_r (p; p) \]
\[ Q(p) = Q_r p (2 - p; p) \]

In calculation of Jacobian, A. ARAKAWA's method is employed.

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日本を中心とした東アジアにおける大気大循環の動気候学

朝 倉 正

本論は日本における梵天気と東アジアにおけるの大気大循環との関係を動気候学の立場から論じたものである。その内容は次の3部に分かれる。すなわち、(1) 日本における梵天気と上層気流型との統計的関係、(2) 東アジアにおける特徴的な上層気流型の形成とその動気候学、(3) 梅雨型気流型の形成とスペゲ高原付近における大気の環流と熱源との関係。

つぎにそれらの要旨を述べる。

日本の梵天気と東アジア上空の気流型には密接な関係がある。気流型を系統的に分類すると、高指数帯状流、中指数帯状流、谷型、波型、夏型、阻塞型に分けられる。また日本の異常気候はしばしば帯状流型と阻塞型の気流型のときにおきるが、これらの特徴的な流れはヨーロッパやアメリカ上空の気流型とも偏西風波動によって互に関連しておきている。統計的にしばしばも中央ヨーロッパと東日本の冬季気候はよく似た変動をくりかえしている。これは偏西風波動の内部相関があってヨーロッパ尾根一中近東谷一東アジア帯状という偏西風波動の配列になっているためである。

阻塞型気流型は寒波吹出し、梅雨、秋霖という東アジアに特有な天候と密接に関連している。この型が形成される緯間的経過を動気候学的に解析すると、この気流型は東アジアだけに局限して存在するのでなく南北球間での互に関連しあって生起し維持されている。たとえば冬前後は阻塞型気流型はつきのような段階で形成される。(1) 8月末頃から台風が日本付近を北上し偏西風帯に突入する。それまで帯状であった偏西風帯によいながらも新しい谷が形成され、台風が運んできた暖気を北方に輸送する。(2) 東方の尾根が強化され、その影響は夏期ひまわりの速さで伝播し北半球をとりまく偏西風帯の谷や尾根が発達する。

(4) 北極地方に蓄積されていた冷気は谷にそって南下し低鋭度地方の暖気は尾根にそって北上し東西方向の運動を阻害するようになる。(5) そして寒にはオホーツク海付近の暖気団は南の暖気団と分離してここに阻塞型気流型が形成されて日本に秋霖がもたらされる。

冬季の阻塞型気流型の形成は秋霖の場合と異なる。冬季高緯度地方の気候はいちらしく冷やされ、低緯度地方の気候は加温されるので南北方向の温度傾度は大きい。寒気が北極地方に蓄えられ冷やされる間は帯状流が強く日本の冬も温暖である。しかし南半の温度傾度がある程度以上では巡る不規則な熱交換がおこる。この熱交換は南ヨーロッパ上の気圧の尾根の形成によって始められる。この尾根は発達しながら北西方向に移動しイギリスを経てグリーンランドまで達し偏西風を阻害する。この変形のためヨーロッパ上に谷、西ヨーロッパと北米西岸に尾根が発達する。これら2つの尾根は北南方進み差には日本の北方で重複する。このとき東アジアに上空に阻塞型気流型が形成され持続的な北西季節風の吹出が始まる。この変化は偏西風波動の波数2の波が他の波に運動エネルギーを供給し、波数2は帯状流からエネルギーを補給され、帯状流は南北の温度傾度によって維持される。

初夏における日本の大気は典型的な阻塞型気流型の形成にともなってはまる。この季節西岸では南西モンスーンの雨期が始まる。これはチャベット高原付近を通る偏西風帯が北上する季節変化と関連している。また、オホーツク海気圧、九州南方の低压帯と印度のモンスーン低気圧との間には相互に関連的に有意な
関連をもと、南西モンスーンが活発になると梅雨も活発になる。このように梅雨と南西モンスーンとはかなり離れた地域の季節現象であるにもかかわらず、統計的に有意な関係があるのは、チベット高原上の大気が流の変動が直接的に南西モンスーンを支配しているからである。問題的には前西風の変動を通じて東アジアの気候に有意な影響をもたらすためである。チベット高原付近の大気圧型循環が強いほど、梅雨期には東アジアの阻塞型気流系が強く夏期には北日本冷夏西日本干魃・暑夏型の気流型が形成される。

また、熱的条件ではチベット高原付近は大規模な熱源、東方洋上に冷源があり、日本はその中間で位置している。熱的効果をみるために北半球 1000, 700, 500 mb の 3 層を用い、外力のように冷熱源を作用させその影響を電子計算機によって算出した。その結果はつきのようにまとめられる。

(i) 日本の東方洋上の冷源だけを作用させると弱い尾根がオホーツク海付近に形成されるが、偏西風に流され停滞しないので梅雨型気圧配置は形成されない。

(ii) チベット高原付近の熱源を作用させ東方洋上の冷源を作用させないと印度付近に定常的な台が形成される。これはモンスーン・トラフに対応するものであろう。しかし、東アジアには阻塞型気圧配置は形成されない。

(iii) チベット高原付近の熱源と東方洋上の冷源を一緒に大気に作用させると印度付近に定常的な台、東アジアに阻塞型気流系が形成される。

さらには、これら熱冷源両方の共同した働きによってはじめて阻塞型気流系が形成されると同時に南西モンスーンと梅雨が関連している原因の一つになっていることを物語っている。あとの梅雨型はオホーツク海高気圧が温暖である観測事実から批判的であるが、印度の熱源を考慮に入れて再評価する必要がある。