Vol.12 No.2 Advances in Atmospheric Sciences May 1995

The Early Summer Seasonal Change of Large–scale Circulation over East Asia and Its Relation to Change of The Frontal Features and Frontal Rainfall Environment During 1991 Summer

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Received October 17, 1994; revised November 15, 1994

ABSTRACT

By using the rawinsonde data, upper cloud amount data and objective analysis data for global domain which all were produced by Numerical Prediction Division, JMA and by using daily and mean weather map issued by JMA and daily rainfall data over the Huaihe River Basin from China, an observational study to the early summer seasonal change of large–scale circulation over East Asia and its relation to change of the frontal features and environment for the frontal rainfall has been carried out. Following reaults have been obtained: (1) The early summer seasonal change of large–scale circulation was occurred during 20–23 May 1991, which was about 10 days earlier than the normal. During the period the subtropical westerly jet and tropical easterlies abruptly moved northward; (2) The northward movement of the tropical easterlies was not uniform, it was earlier at 100 hPa level and about 24 hrs late at 200 hPa level. The phenomenon was associated with earlier disappearence of the subtropical westerly jet at 100 hPa level; (3) During the seasonal change there were two westerly jets in the upper level and changed their intensity with the time. Before 18 May 1991, the southern one was more intense and then changed to more intense for the northern one and disappearence of the southern one, the phenomenon seemed to be appeared as northward movement of the southern jet; (4) A faster temperature (*T*) rising in the upper level over the Tibetan Plateau was associated with the seasonal change. From the *T* rising the *T* maximum moved onto the plateau, changing the *T* gradient from positive to negative to the south flank of the plateau, the effect to reduce and disappear the southern westerlies. Also the *T* rising was associated with change of the frontal features over East Asia; (5) The seasonal change type during 1991 was same as that during 1992 and 1993, but different from that during 1990; (6) The environment for the frontal rainfall was change in the season, the differences were in the baroclinity in upper level and vertical wind speed and direction shear.

Key words: Seasonal change, East Asia, Rainfall, mei–yu front

I. INTRODUCTION

1991 was one of the most severe flood years in the Changjiang–Huaihe River Basin over East China. The flood was caused by receiving too much rainfall in the rainy season which is called the mei–yu season in China. The mei–yu season in 1991 was characterized by following features: earlier arrival, longer period and more strong rainfall intensity (Ding, 1993).

East Asia is a noted monsoon region. Its remarkable feature is seasonal northward shift of the major rainfall belt with the summer monsoon onset (Tao and Chen, 1987). When the

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①Visiting Institute for Hydrospheric–Atmospheric Sciences, Nagoya University, Japan from Department of Geography, Hangzhou University, Hangzhou 310028, P. R. China rainbelt moves in and becomes stationary over a part of the region, it is the major rainy season and very important for the water supply in the area. Therefore, East Asia is very sensitive to the anomalous change of climate which will influence the water cycle over the region and cause flood and drought event.

It this study we intend to investigate the early summer seasonal change of large–scale circulation during 1991 and its relation to the change of frontal features and the evironment for the frontal rainfall.

As we have mentioned that one of the features for the 1991 mei–yu season was its early arrival. Many studies have showed that the onset of the Indian SW monsoon and the mei–yu season over China is closely related to the early summer seasonal change of large–scale circulation. The change is characterized by a rapid transition or abrupt change. Following phenomena have been discovered, which are some of the abrupt changes:

(1) An abrupt northward movement of the upper subtropical westerly jet from the south to north flank of the Tibetan Plateau (Yin, 1949; Murakami, 1958; Zhao et al., 1984);

(2) A northward advance of the upper tropical easterlies associated with the northward movement of the westerly jet. The easterlies established in the upper troposphere over southern and southeastern Asia (Tao et al., 1958; Ye et al., 1959) and tropical Pacific (Neyama, 1963);

(3) Establishment of a planetary–scale upper anticyclone over the Tibetan Plateau, which is formed by moving poleward from northern Malaysia in May and increasing its scale (Krishnamurti et al., 1976; Krishnamurti, 1985);

(4) An abrupt development of an anticyclone above 300 hPa and an abrupt increase of 300 hPa temperature near the Afghanistan–Western Tibet border in the first week of June in 1979. It happened before two weeks of the onset of the SW monsoon (Murakmi and Ding, 1982; Ninomiya et al., 1986);

(5) Some abrupt change of the frontal features over East Asia: the front firstly becomes quasi–stationary, then disappears its horizontal temperature gradient, the front is characterized by the moisture contrast and the frontal zone becomes moist convective instability (Ninomiya, 1984; Kato, 1985, 1987; Kato and Kodama, 1992).

About the cause of the seasonal change, many studies have considered that it is related to the thermal effect of the Tibetan Plateau (Murakami, 1987; Flohn, 1968; Luo and Yanai, 1983; Chen et al., 1985; Yanai, 1992; Ye and Gao, 1979; Zhu, 1957).

In our study a difference to the previous studies is that we will study the seasonal transition process by daily map and change in different level, therefore, it may discover some aspects we don't know before for the change.

Meantime, one of our major purposes is to discuss the water cycle associated with the seasonal change. So we will take a study on the environment for the heavy rainfall development associated with the seasonal change.

Following data are used in the present study:

(1) The rawinsonde observation data in 1991 (TEMP–A) extracted from the sorted data (refer to as SD data) edited by Numerical Prediction Division of Japan Meteorological Agency (JMA);

(2) Upper level cloud amount (amount of clouds whose tops are above 400 hPa level definded in every 0.5° × 0.5° Lat–Long. domain based on GMS infrared observations), which are also extracted from SD data;

(3) The operational objective analysis data by Numerical Prediction Divsion of JMA for global domain (refer to as GA data). The data were in every 1.875° × 1.875° Lat–Long.

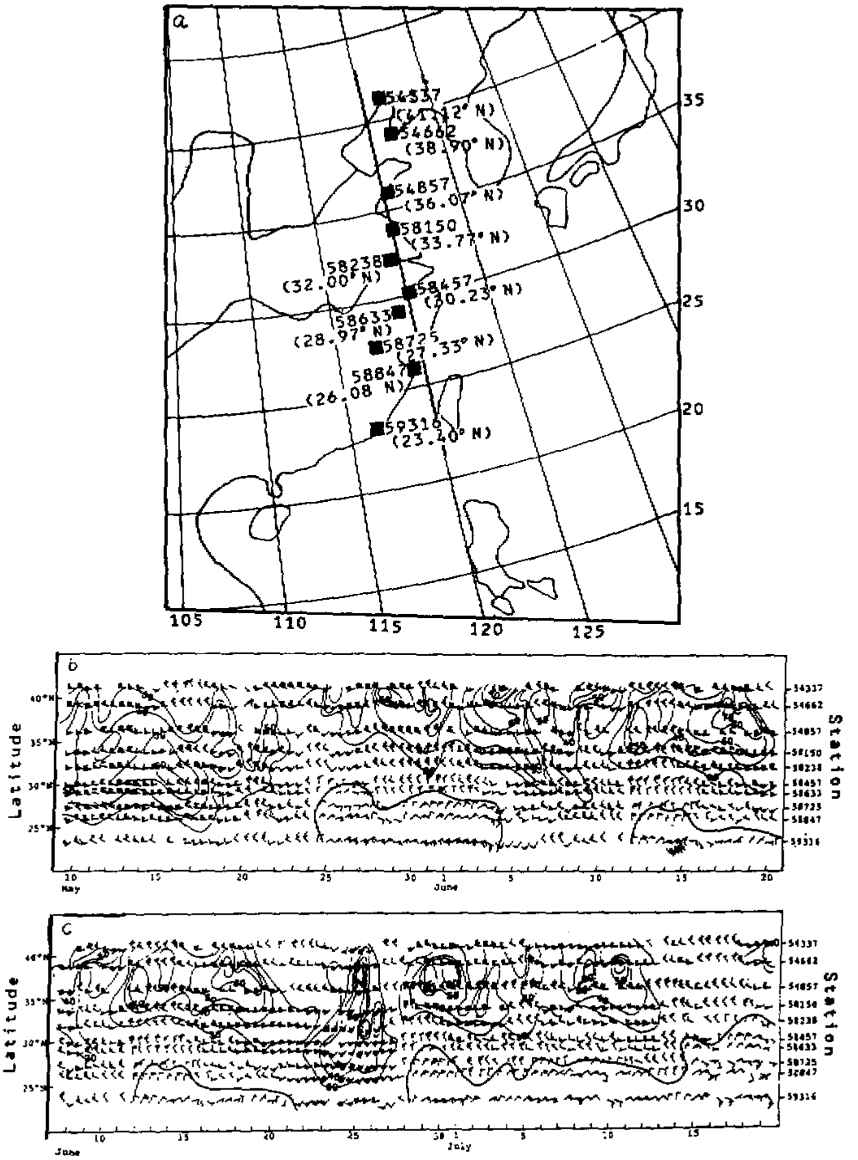


Fig. 1. Time–latitude cross–section of 200 hPa wind near 120°E during early May to late July 1991. a) Station location; b) 10 May to 20 June 1991. Heavy solid line marks the boundary between the westerlies and easterlies. Thin solid lines are isotach with contour interval 10 m / s. Full and half barbs in wind arrows represent 10 and 5 m / s, respectively. c) 8 June to 19 July 1991. figure description is same as Fig. 1b.

network and at 17 standard pressure levels;

(4) Daily and mean weather maps issued by JMA;

(5) Daily precipitation data at 40 stations over the Huaihe River Basin collected directly from China.

II. THE EARLY SUMMER SEASONAL CHANGE OF LARGE–SCALE CIRCULATION DURING 1991

Fig. 1 shows a time–latitude cross–section of 200 hPa wind near along 120°E during the period from early to middle summer 1991. Before 23 May the maximum westerly belt or westerly jet was around 30°–35°N. The jet abruptly moved northward to north of 35°N around the date 23 May, during the same time the tropical easterlies moved to north of 25°N after one or two days. These phenomena marked the early summer seasonal change of large–scale circulation from winter to summer and entered the mei–yu season over East Asia (Ye et al., 1959). After this change, the westerly jet was maintained to the north of 35°N, sometimes, it moved toward south and dropped the easterlies out of the land region.

The early summer seasonal change during 1991 was quite early than the normal which is during early June according to Ye et al. (1959).

We also take a look at the upper anticyclone evolution during this priod. Fig. 2 gives the 5–day mean 100 hPa height during May to July 1991. A significant change occurred during the period from 21–25 May, the high over the South China Sea started to abrupt expansion. After that time the high largely increased its domain and extended toward west, however, its center moved onto the Tibetan Plateau till late June. We have noticed that this expansion was an event before onset of the Indian SW monsoon because it was before the formation of the Tibetan Plateau high, but the expansion was corresponded to the northward movement of the westerlies and easterlies over East Asia, which was related to the beginning of the mei–yu season. We like to call this expansion as an explosive development of 100 hPa high. Also we like to indicate here that there was another large enhancement of the 100 hPa high during the period from 15 to 19 July 1991, this was just the period the end of the mei–yu season 1991 according to Ding (1993). In this study we will not study this mid summer change.

It is interesting to understand the process on the abrupt change mentioned just above. We have constructed the wind field at 100 and 200 hPa level over the subtropical region of East Asia. Fig.3 presents the wind field during 0000GMT 23 May to 1200GMT 26 May 1991. At 0000GMT 23 May the area was dominated by the westerlies both at 100 and 200 hPa level except over the South China Sea. Change was occurred at 100 hPa level at 1200GMT 23 May,

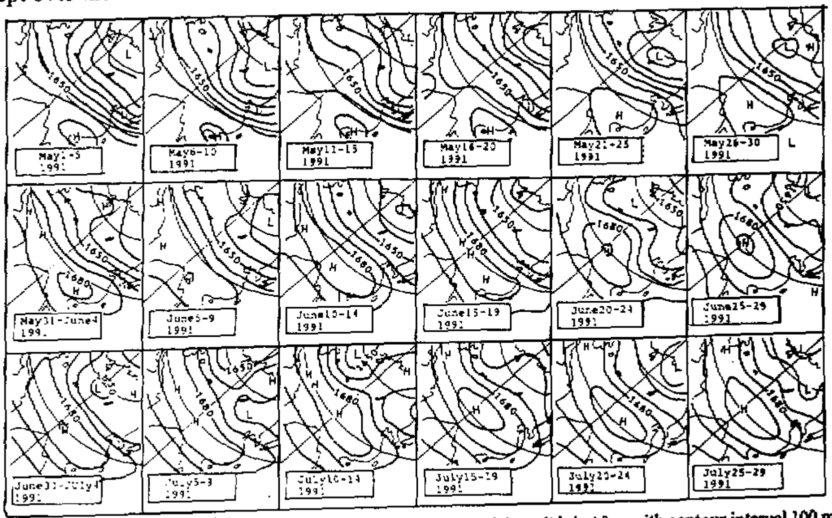
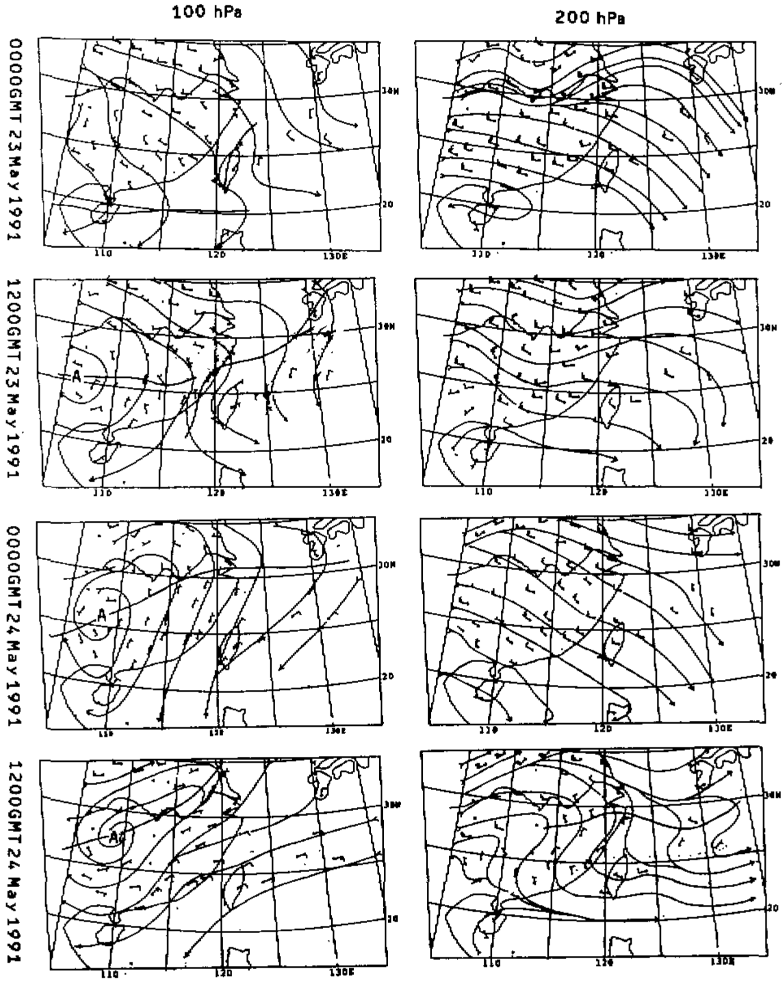


Fig. 2. 5–day mean 100 hPa height during May to July 1991. Height unit is in 10 m with contour interval 100 m.

theeasterlies abruptly established over the land region south of 25°N, in the meantime, the westerlies still maintained at 200 hPa level. It can be seen that a limited easterly area occurred at 200 hPa level at 1200GMT 24 May, 24 hrs later than the occurrence of the easterlies at 100 hPa level, and increased its domain at 0000GMT 25 May. After 25 May the land region over Southeast China was dominated by the easterlies both at 100 and 200 hPa level, however, the boundary between the westerlies and easterlies sloped northward from 200 to 100 hPa level.

This fact showed that during the seasonal change the northward movement of the tropical easterlies was not uniform, it was earlier at 100 hPa level, then followed at 200 hPa level, for the 1991 case the time interval was about 24 hrs.

Another aspect in Fig. 3 was that the anticyclone at 100 hPa level did not move toward the Tibetan Plateau in the daily wind field as seen in the time mean map (Krishanmurti, 1985), oppositely, its centers moved toward east one by one and merged over East Asia to form a rather large anticyclone. We think this process and its relation to form the Tibetan Plateau High need to take future study.



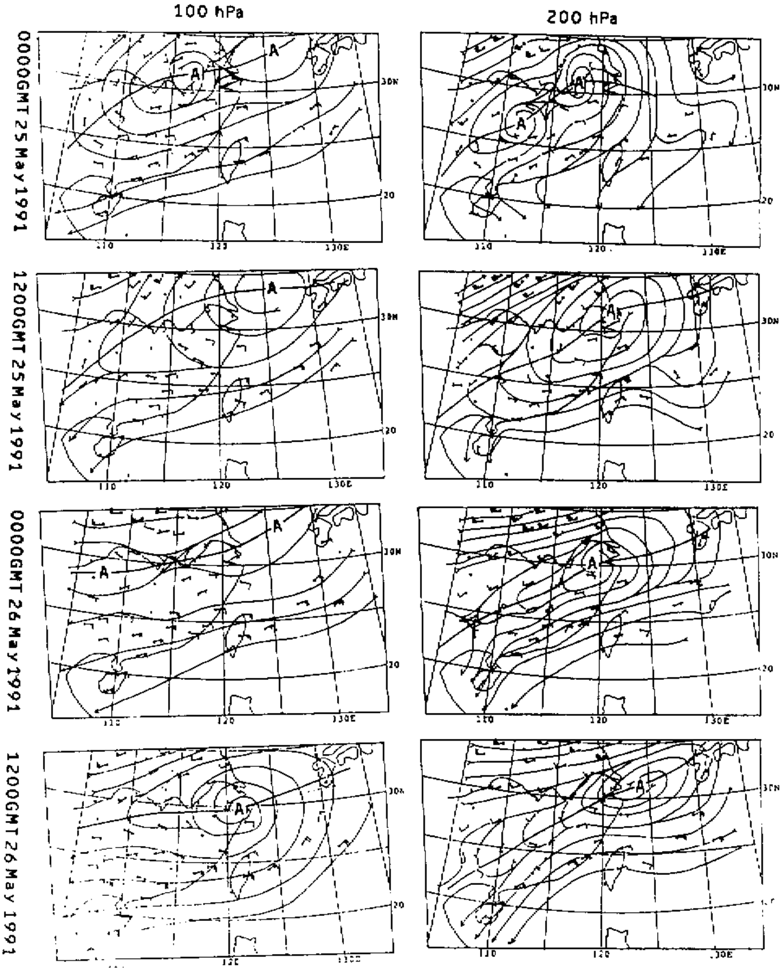
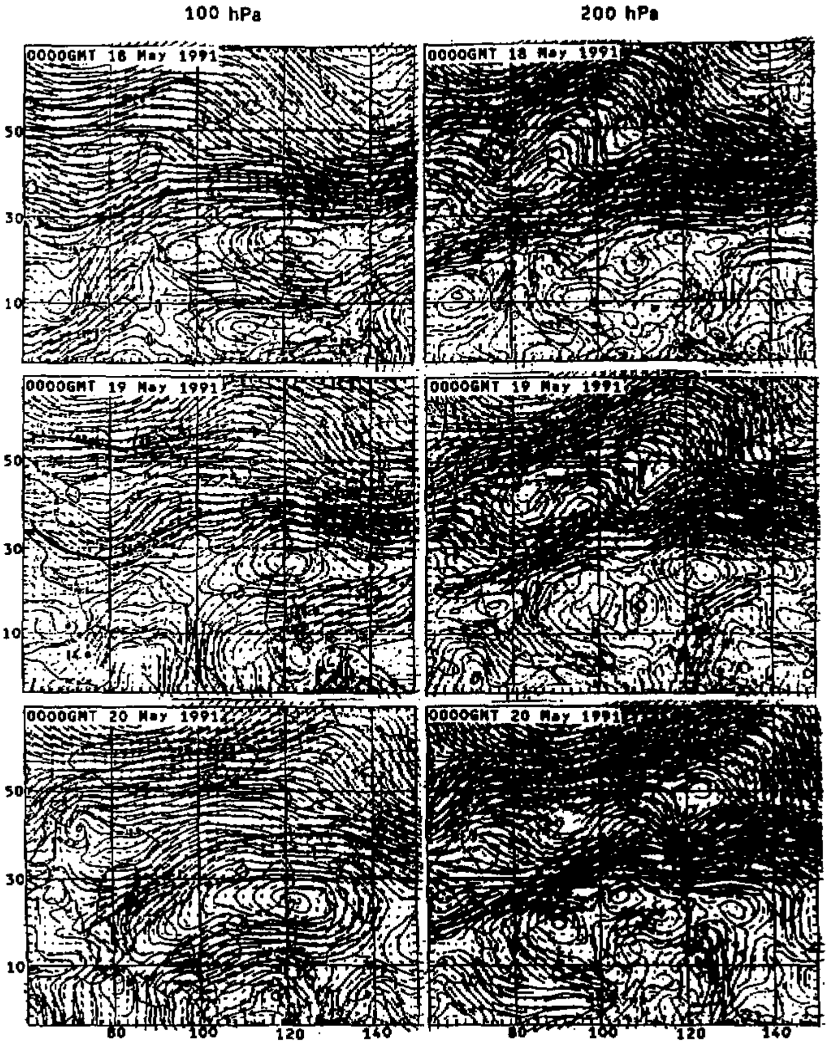


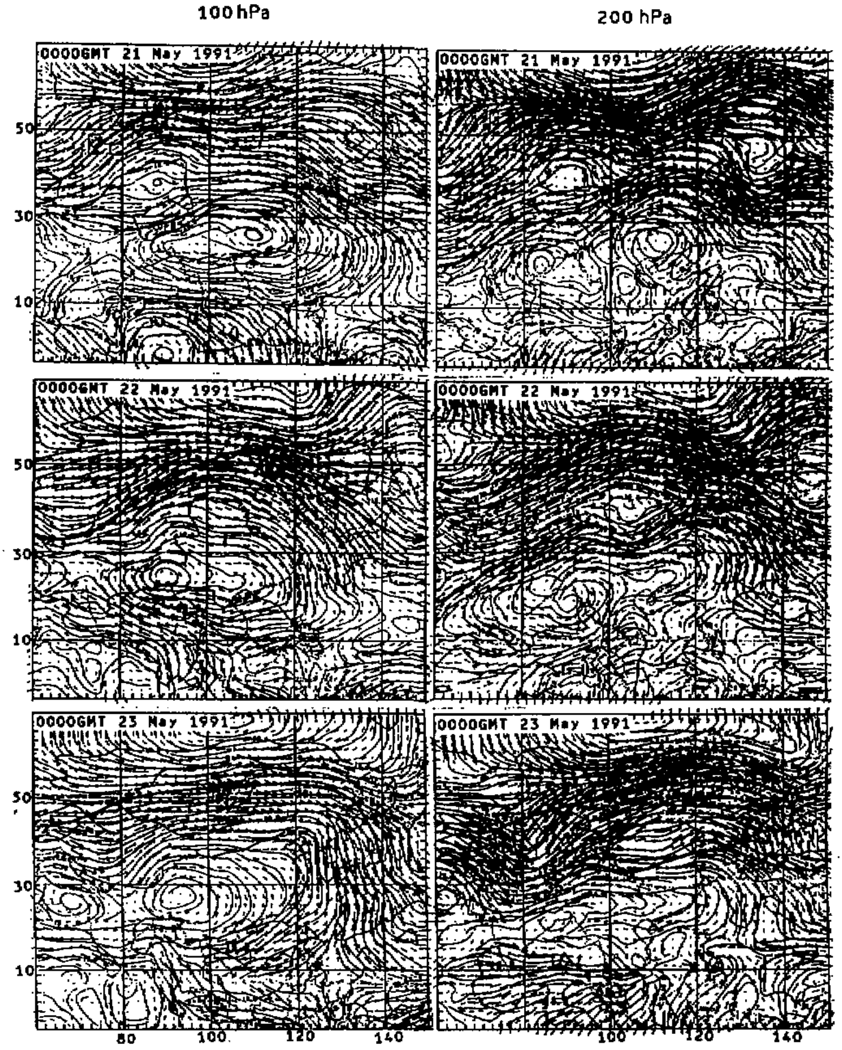
Fig. 3. Wind field at 100 and 200 hPa over subtropical East Asia during 0000GMT 23 May to 1200 GMT 26 May 1991. Wind arrow description is same as Fig. 1. Heavy siold line marks the boundary between the westerlies and easterlies.

Now, we go to further study, what are the related circulation creating the northward movement of the easterlies earlier at 100 hPa level. Then we have produced wind field in the domain of Asia and its surrounding area at 100 and 200 hPa level during the period from 0000GMT 18 May to 0000GMT 26 May 1991 based on the GA data (Fig. 4, the maps at 1200 GMT were not shown). The wind field at 0000GMT 18 May was in same situation as it during 15–17 May (figures were not shown), the remarkable feature was that there were two westerly jets with the southern one more intense both at 100 and 200 hPa level. The westerlies were weaker at 100 hPa level than that at 200 hPa level. The southern jet corresponded to the subtropical jet which passed the south fank of the plateau, the major anticyclone was located to the south of it. Change can be seen after 18 May, the northern and southern jet increased and decreased their intensity, respectively. They became nearly equal intense around 0000GMT 20 May, then after that time the northern one became stronger. At 0000GMT 22

May the southern jet decreased to disappear at 100 hPa level but still could be seen at 200 hPa level, where the jet disappeared during 0000GMT 25 May. We can see that the time the southern jet disappeared at these two levels corresponded to the northward movement of the easterlies at the two levels.

This fact indicated that the northward movement of the easterlies was related to the disappearence of the subtropical westerly jet. From Fig. 4 we have seen that the subtropical jet which disappeared in the seasonal change mainly was not through northward movement, it was decreased to disappear. The jet which moved to the north flank of the plateau actually was the process disappearence of the southern jet and enhancement of the northern jet. This is a different concept from the jet moved to the north in the seasonal change.

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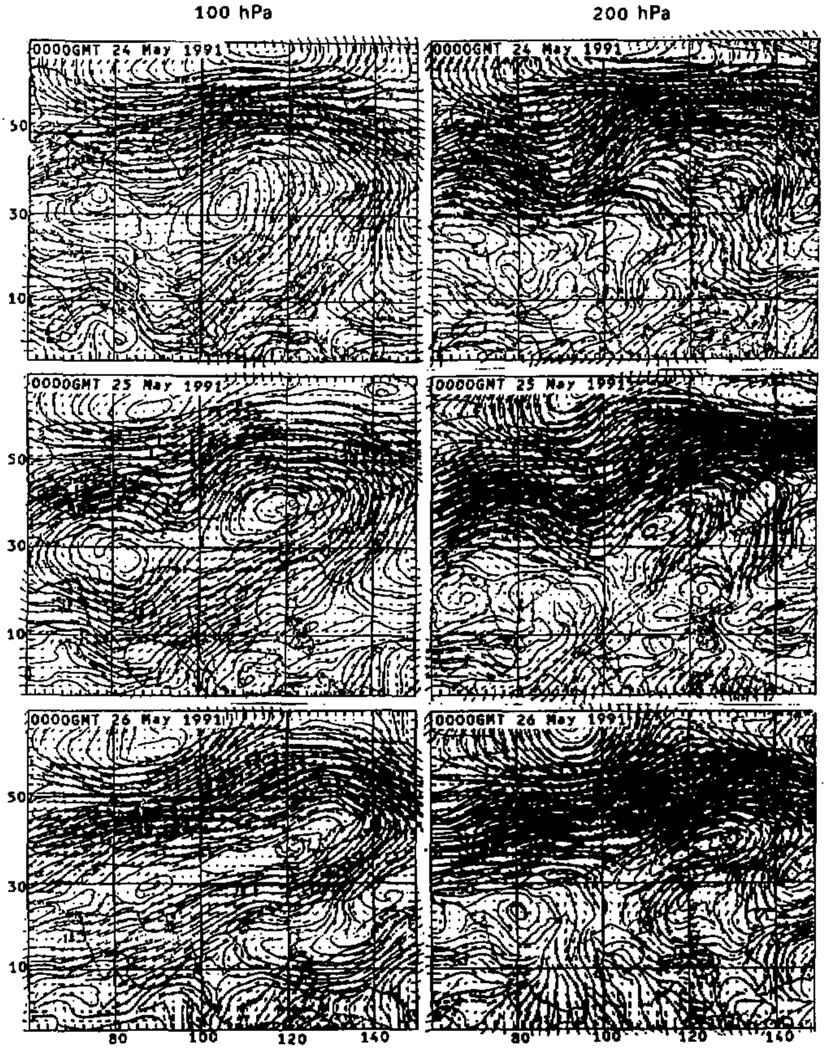

Fig. 4. Objective analysis wind field at 100 and 200 hPa during the period from 0000GMT 18 May to 0000GMT 26 May 1991. Thin line is streamline. Heavier solid line is isotach with contour interval 10 m / s. Heavy arrow indicates the maximum wind axis or jet.
a) 18 to 20 May; b) 21 to 23 May; c) 24 to 26 May.

We have noticed that the change of the southern jet was through two steps: first, decrease of the intensity and then disappearence of it. Kato et al. (1992) discovered two steps existed in the change of frontal features in the seasonal change, the front firstly became quasi–stationary because of decrease of baroclinity in the westerlies, then it changed to disappear the horizontal temperature gradient. The connection between these two phenomena needs to identify.

III. CHANGE OF TEMPERATURE FIELD IN RELATION TO THE CHANGE OF LARGE-SCALE CIRCULATION

Many researchers considered that the early summer seasonal change over the southern Asia is closely due to the thermal effect of the Tibetan Plateau (Flohn, 1976; Murakami, 1987; He et al., 1992). This is because during summer, the Tibetan Plateau due to its extremely high elevation receives a large amount of solar radiation which effectively heats th mountain surface. The upper tropospheric heating by the plateau may exert a strong influence to the seasonal change of large-scale circulation. Therefore, we intend to take a look at change of the upper level temperature field and its relation to the circulation change.

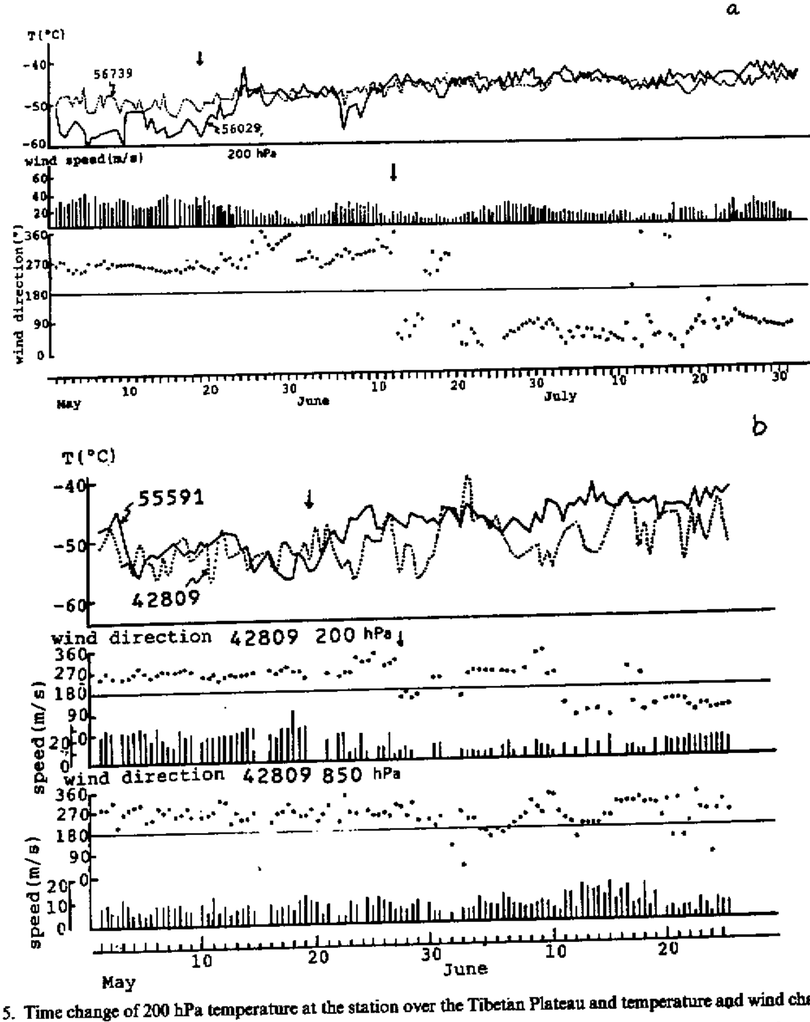

Fig. 5. Time change of 200 hPa temperature at the station over the Tibetan Plateau and temperature and wind change at a station south to the plateau. a) Plateau station 56793(33°06′N, 96°45′E, height 3704 m) and southern station 56739(25°07′N, 98°29′E, height 1649 m); b) Plateau station 55591(29°42′N, 91°08′E, height 3659 m) and southern station 42809(22°39′N, 88°27′E, height 4 m).

Fig. 5 shows time change of 200 hPa temperature (*T*) respectively at two plateau stations 56029 (33°06′N, 96°45′E, height 3704 m) and 55591 (29°42′N, 91°08′E, height 3659 m) with time change of the temperature and wind at one of their southern stations which respectively are station 56739 (25°07′N, 98°29′E, height 1649 m) and 42809 (22°39′N, 88°27′E, height 4 m). We have seen that an abrupt 200 hPa *T* rising at the plateau stations occurred around 20 May 1991 and ended around 23 May 1991, the *T* rose about 5°C during this period. This ended time corresponded to the time the northward shift of the subtropical westerly jet in Fig. 1. From this rising, the *T* in the upper level of the plateau became higher than it in the southern region (Fig. 5b) or nearly same (Fig. 5a). This fact indicated faster 200 hPa *T* rising over the plateau and the change displayed abrupt feature. From the wind change at the southern stations, we have seen that the *T* rising had clear influence on the circulation, stable and strong SW wind before the rising transferred to unstable and weak westerlies and sometimes later changed into easterlies. From Fig. 5b we can see that the 200 hPa *T* rising over the plateau was ahead of the onset of the SW monsoon over northern India because 850 hPa wind at station 42809 (in northern India) was changeable and rather weak during the period.

We can consider that the effect of the 200 hPa *T* rising over the plateau may change the *T* gradient. Because of the faster *T* rising over the plateau, the *T* gradient south of the plateau became negative from positive, therefore, led to decrease and disappear the westerly jet. With this idea, the 200 hPa *T* field, in the period from 0000GMT 20 May to 0000GMT 25 May 1991 was provided in Fig. 6 (the maps at 1200GMT were not shown). Before 20 May, the maximum *T* at 200 hPa level was found to the east of the plateau. The south flank of the plateau was located in a positive *T* gradient rgeion. After 20 May, the *T* over the plateau rose quickly and reached –45°C at 0000GMT 23 May from –49°C at 0000GMT 21 May. After this rising the *T* field changed with its maximum moved onto the plateau, the south flank of the plateau became a negative *T* gradient region. This change gave an effect to reduce the westerlies south of the plateau and the time just corresponded to disappear the subtropical westerly jet around 23 May in Fig. 1. This phenomenon was indicated also by Murakami et al. (1982). So we can have a point of view that the abrupt *T* rising in the upper level of the plateau seems to be a trigger to the early summer seasonal change. Many works (Yanai et al., 1994; Murakami, 1987) considered that the upper *T* rising over the plateau is due to the dry convection before the onset of monsoon, it transfers the sensible heat from ground to the upper level. We have noticed the fact that the *T* rising during 1991 was just happened after a period with no or very few upper cloud amount over the plateau region during mid May 1991 (see Fig. 13), so the plateau surface would receive more solar radiation, was favorable for occurrence of the dry convection and led to the *T* rising in the upper level.

We also examine that there is any connection between the plateau *T* rising and the change of the frontal features over East Asia. Fig. 7 shows a time series of *T* field at surface , 850 hPa and 500 hPa level during the period from 0000GMT 20 May to 1200GMT 22 May 1991. It has been seen that at 0000GMT 21 May and before, the frontal zone from surface to 500 hPa level was integrated and tilted northward with height. It is noticed that from 0000 to 1200GMT 21 May, the frontal zone at 500 hPa level suddenly moved northward and separated with that at 850 hPa level and surface. Then the features of the mei–yu front were formed, of which it was a shallow front indicated by the TAMEX studies (Ray et al., 1991; Chen et al., 1989), a warm tongue was over the front (Ninomiya and Murakami, 1987). Figs. 8 and 9 show the 10–day mean *T* field from surface to 200 hPa level during the period 11–20

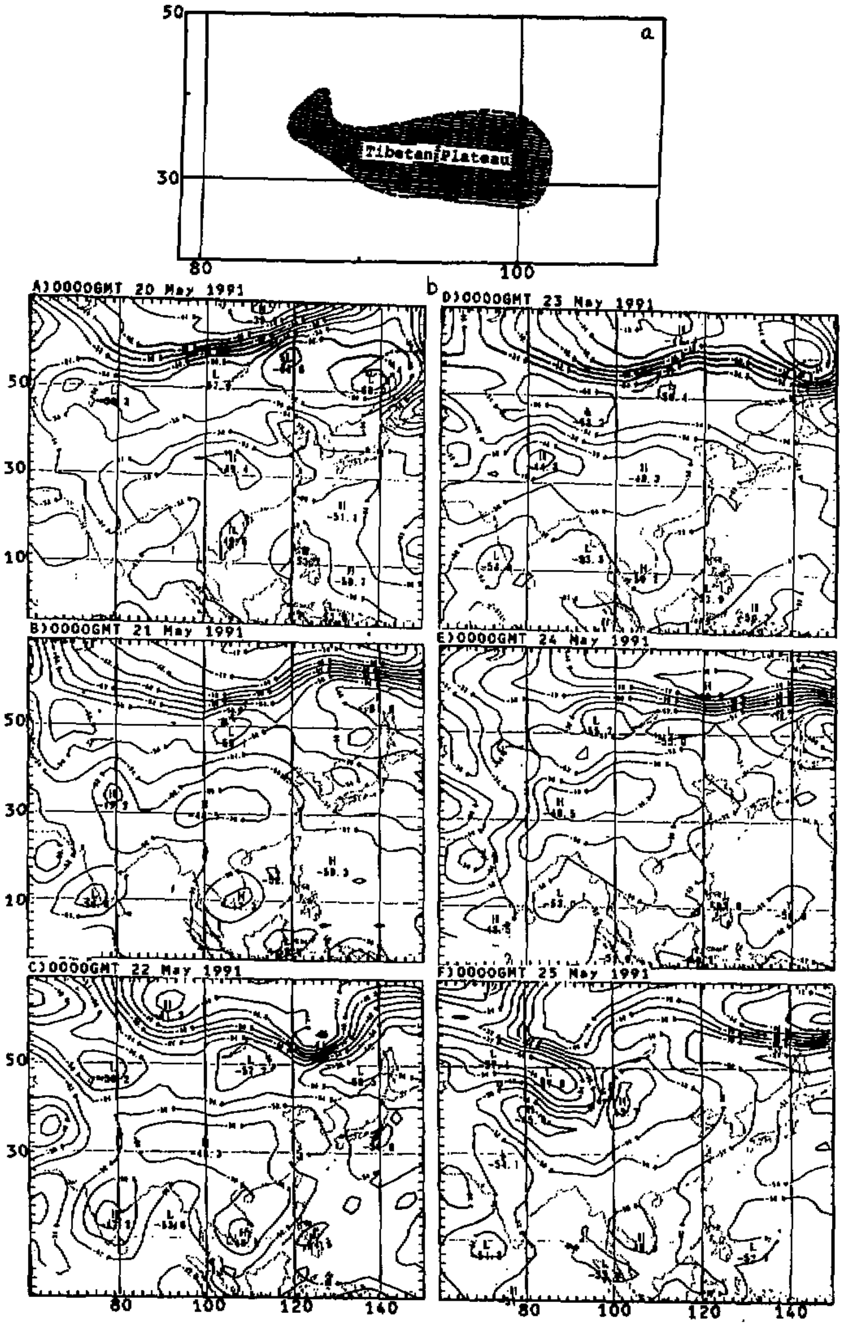

Fig. 6. 200 hPa temperature field during 0000GMT 20 May to 0000GMT 25 May 1991. a) Location of the Tibetan Plateau. Shaded area is the plateau over 3 km. b) 200 hPa temperature field. Contour interval is 2°C.

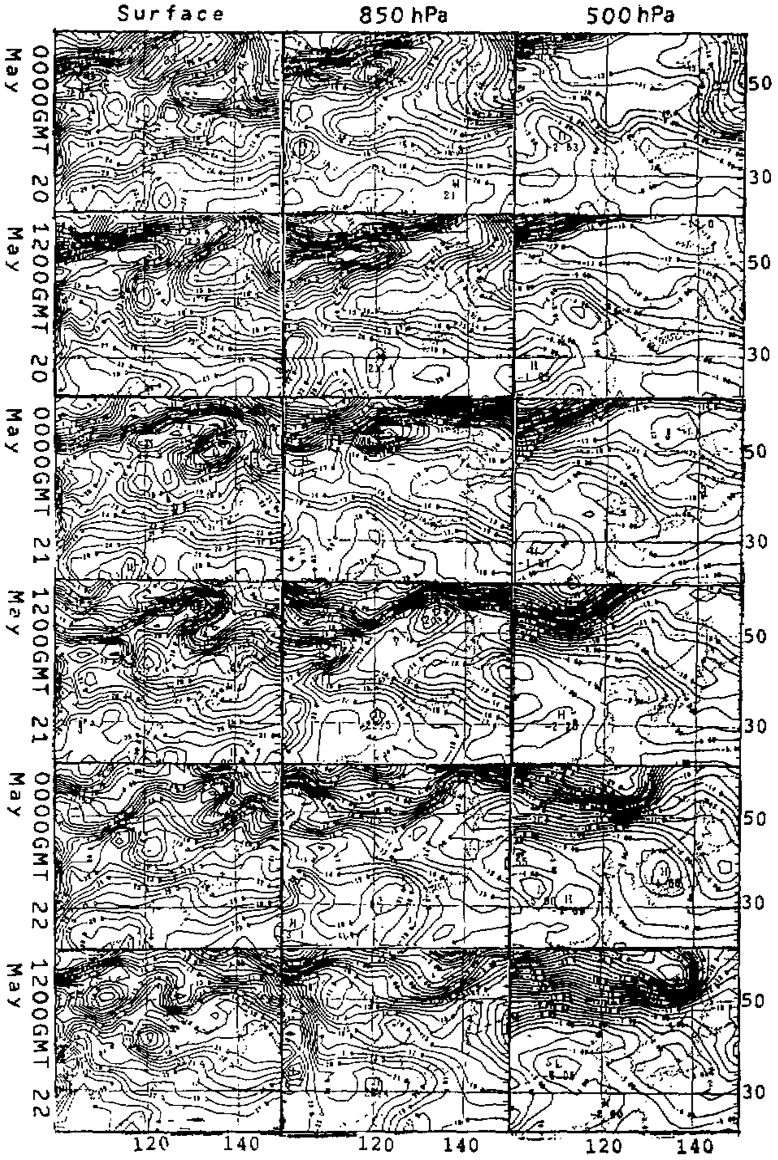

Fig. 7. Temperature field at surface, 850 hPa and 500 hPa during 0000GMT 20 May to 1200GMT 22 May 1991. Contour interval is 1°C.

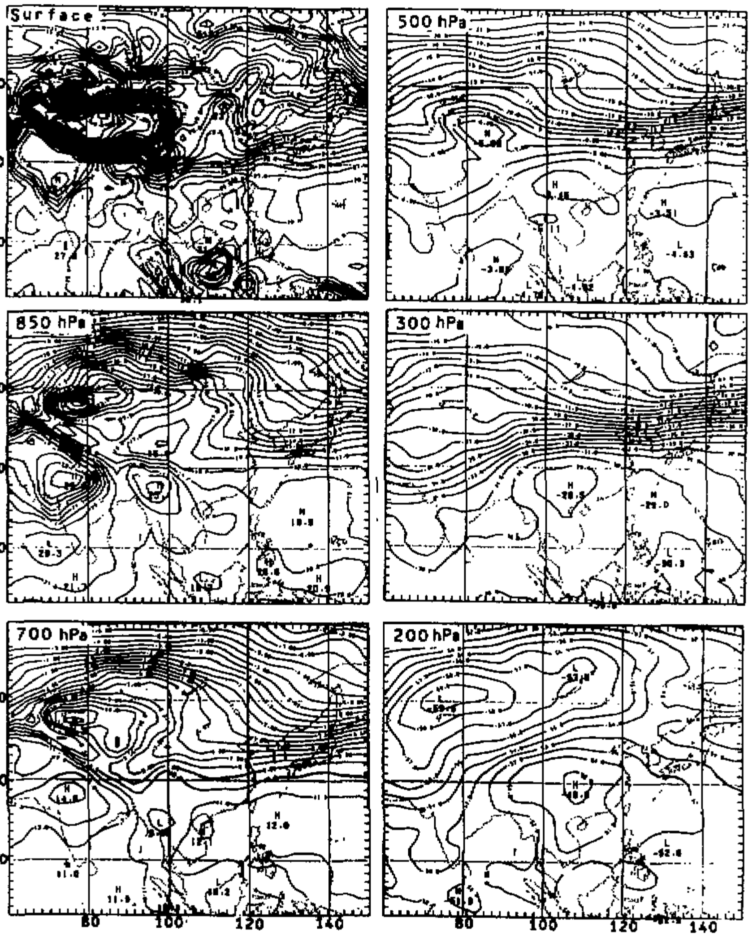

Fig. 8. 10–day mean temperature field for 11–20 May 1991, referred to before the seasonal change. Contour interval is 1°C.

May 1991 and 25 May –4 June 1991, which were respectively represented of the structure of vertical *T* field just before and after the seasonal change. The difference can be described as followsing:

(1) Before the change (Fig. 8), the frontal zone over East Asia was deep, extended from surface to 200 hPa level and tilted northward with height. After the change (Fig. 9), the frontal zone above 700 hPa level shifted northward, separated from the frontal zone below it. Then the frontal zone over subtropical East Asia became very shallow;

(2) Before the change (Fig. 8), the *T* maximum above 300 hPa was over the southern China. After the Change (Fig. 9), it moved onto the plateau region. This change displayed the thermal effect of the plateau and caused the frontal zone disappearence to the south and enhancement to the north of the plateau in the upper level.

Then we have seen that the Tibetan Plateau plays a very important role on the early summer seasonal change.

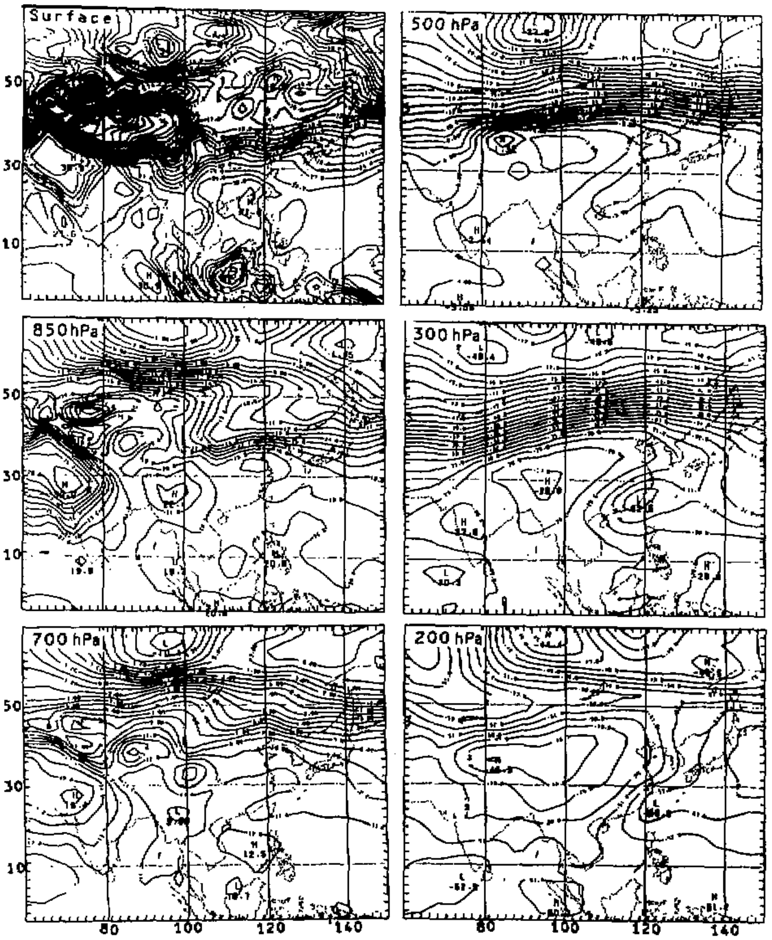

Fig. 9. 10-day mean temperature field for 25 May to 4 June 1991, referred to after the seasonal change. Contour interval is 1°C.

IV. THE EARLY SUMMER SEASONAL CHANGE IN 1990, 1992 AND 1993

We have taken an investigation on the early summer seasonal change in 1991. Anyway this study needs to be verified in other years. For simply, we have taken a look at the 5-day mean 100 hPa height in the weather map by JMA during 1990, 1992 and 1993. It has been discovered that different type of the change existed. The change in 1992 and 1993 was same as that in 1991 but the change in 1990 was a different type.

Fig. 10 shows the 5-day mean 100 hPa height during 1992 and 1993. It is clear that the explosive development of the 100 hPa high both occurred during 31 May-4 June, almost 10 days later than that during 1991. This indicated the early arrival of the mei-yu season in 1991 as we have mentioned. After the explosive expansion, the high continuously increased its domain and extended toward west. So the same type 1991, 1992 and 1993 identified that it can be one type of the early summer seasonal changes.

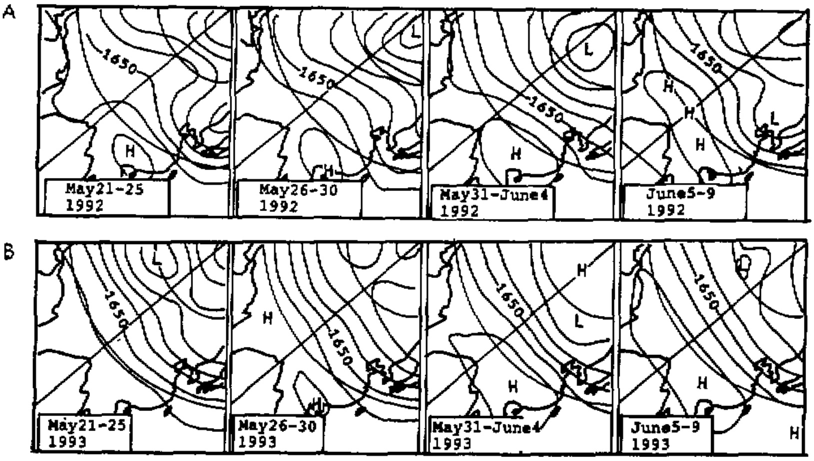

Fig. 10. 5–day mean 100 hPa height. Figure description is same as Fig. 2. From 21 May to 9 June 1992; b) From 21 May to 9 June 1993.

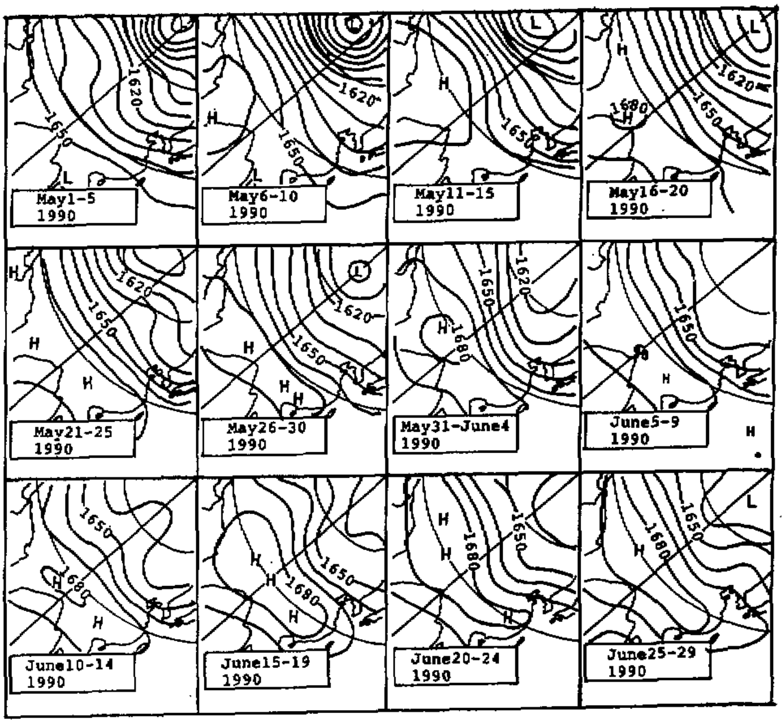

Fig. 11. Same as Fig. 2 except for the period from 1 May to 29 June 1991.

Fig. 11 shows the 5–day mean 100 hPa height during 1990. We can discover that the explosive developmet of 100 hPa high was occurred during 6–10 May and its location was not over Southeast Asia but over India. The further development type also was different, it increased and extended toward east.

From this simple investigation, we have known that there existed different type of the early summer seasonal change. Their implication to the water cycle is an important subject to be studied.

V. THE FRONTAL RAINFALL ENVIRONMENT FEATURES IN THE 1991 MEI–YU SEASON

Since the seasonal change, the front has changed its features. As we have known that the front in the mei–yu season is displayed by following features: quasi–stationary, shallow frontal zone, small horizontal temperature gradient, large moisture gradient, moist convective

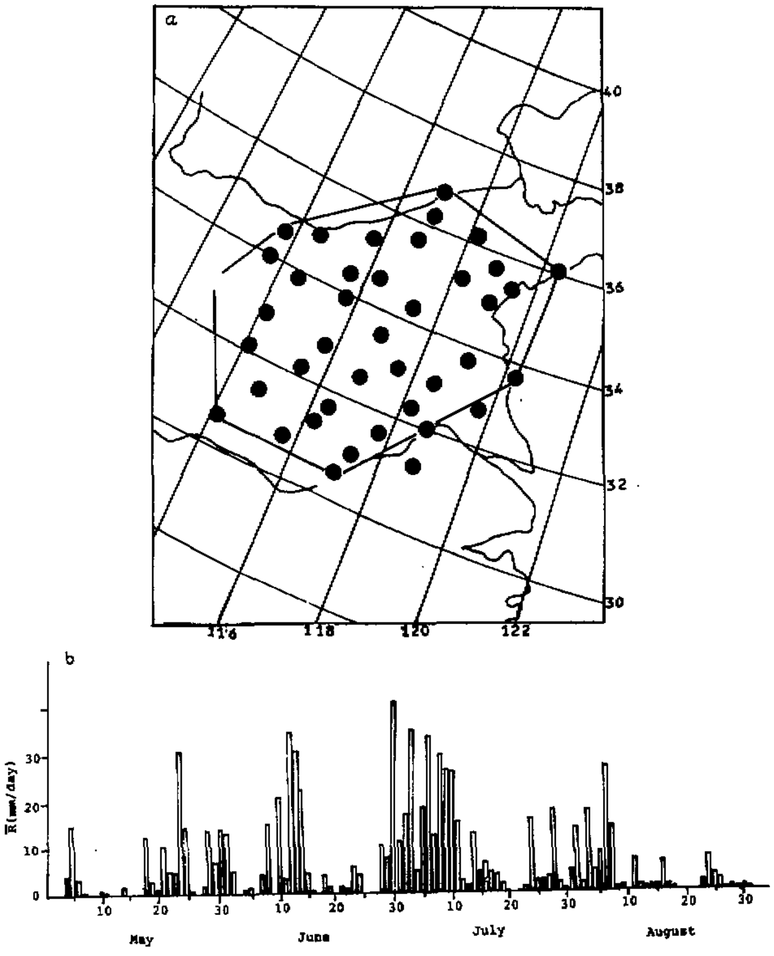

Fig. 12. Time change of daily mean rainfall amount at the 40 stations over the Huaihe River Basin during May to August 1991. Station location; b) Time change of the daily mean rainfall.

instability in the frontal zone and a strong low–level SW flow (LLJ) (Ninomiya, 1984; Kato et al., 1992; Chen et al., 1989). These features are important for the heavy rainfall development.

One the other side, Si (1989) and Yamazaki et al. (1993) indicated that the mei–yu front is experienced different kinds of disturbance from north and south. These disturbances are closely related to the heavy rainfall development associated with the front.

The frontal features and the disturbances on the front depend on the environment of the front. We have noticed that the environment for the mei–yu front heavy rainfall is experienced change in the saeson.

As indicated by Ding (1993), there were 3 major rainfall processes over the Changjiang–Huaihe River Basin during the 1991 mei–yu season, they were in the period 18–27 May, 2–20 June and 30 June–12 July. Fig. 12 shows the time change of mean daily rainfall at 40 stations over the Huaihe River Basin during May to August 1991, the major rainfall was in 21–25 May, 31 May–4 June, 9–14 June and 30 June–14 July. We have noticed

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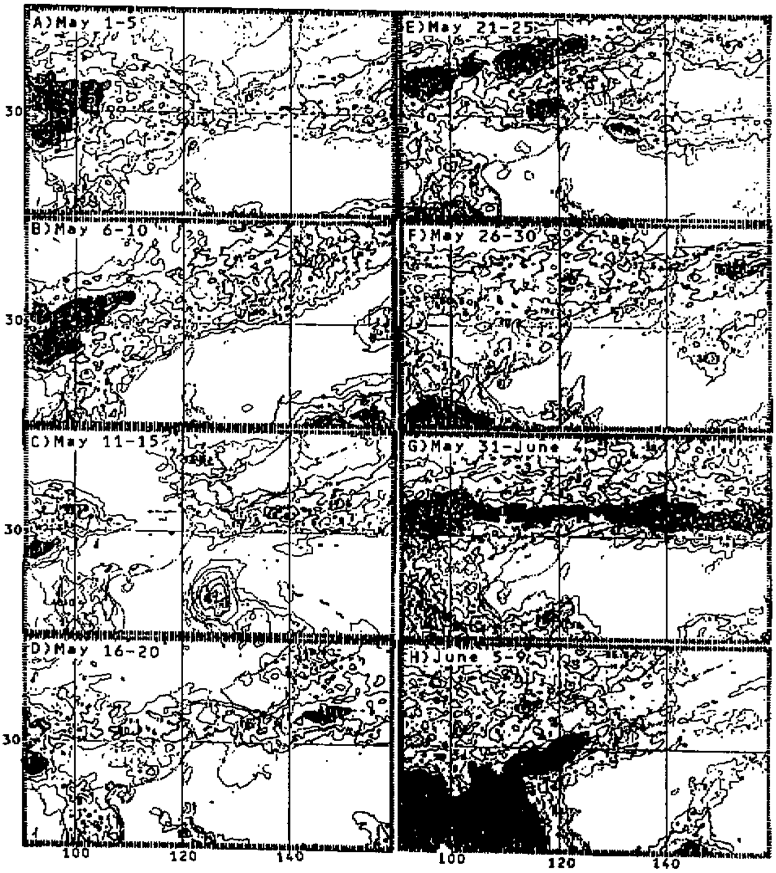


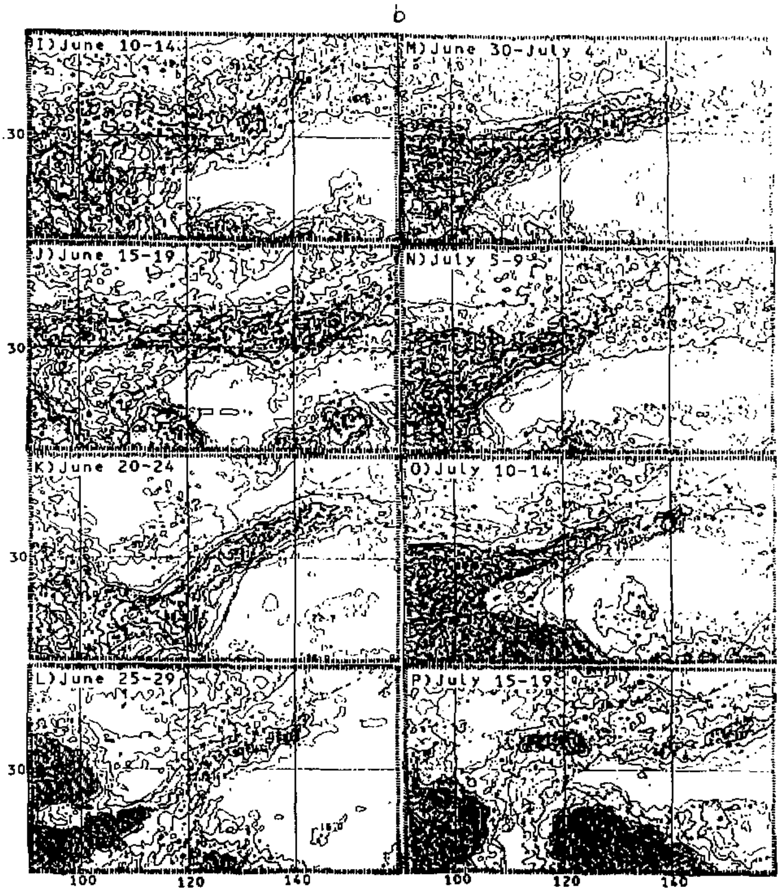


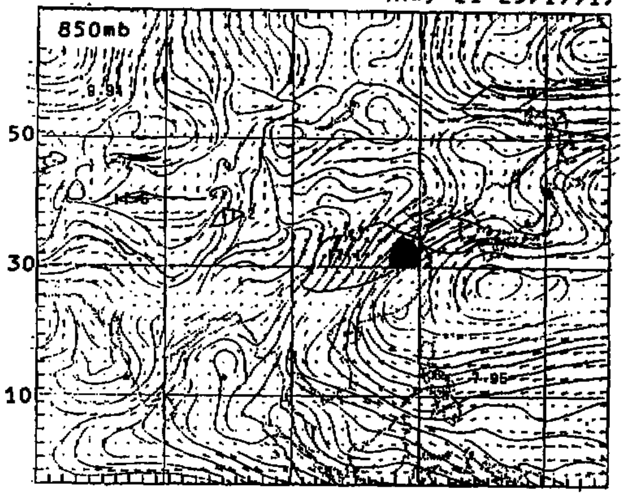
Fig. 13. 5–day mean upper cloud amount during 1 May to 19 July 1991. Unit is 1% and contour interval is 10%. Shaded area is amount greater than 40%.

that there were 3 mei–yu break periods which were in 26–30 May, 5–9 June and 15–29 June. It is interested to discover in Fig. 1 that the 3 break periods all coupled with the southward movement of the westerly jet, in the late two break periods the easterlies had dropped out of the land region.

Fig. 13 shows the 5–day mean upper cloud amount distribution during May to middle July 1991. As we have mentioned, the upper cloud is definded as the cloud top higher than 400 hPa level. According to the cloud formation, these clouds are in association with organized tropical and extratropical cyclonic storms and produce significant precipitation (Cotton and Anthes, 1989). Maruyama et al. (1986) showed the mean upper cloud amount to have proportional relationship with monthly rainfall over the western tropical Pacific. We can see the belt–type of cloud zone over East Asia, it is the frontal cloud belt. It can be seen that during the major rainfall periods, over 40% cloud amount was found in the Huaihe River Basin; during the break periods the cloud belt either decay (26–30 May and 15–19 June) or movement southward (5–9 and 20–29 June). Comparing to the monsoon break over India, of which, it is caused by broad–scale surface pressure trough moving northward (Krishnamurti and Nurgi, 1987), and the mei–yu break has different process, its frontal zone moves southward, opposite to the process of the Indian monsoon break.

To study the environment for the frontal rainfall, we have produced the 5–day mean wind field at 850 and 200 hPa level matched with the cloud amount distribution. It is interested to discover different environment for the frontal rainfall in the season. Three kinds of environment have been identified and the typical cases were given as in the following.

A)5 day mean wind field(May 21-25,1991)



B)5 day mean wind field(May 21-25,1991)

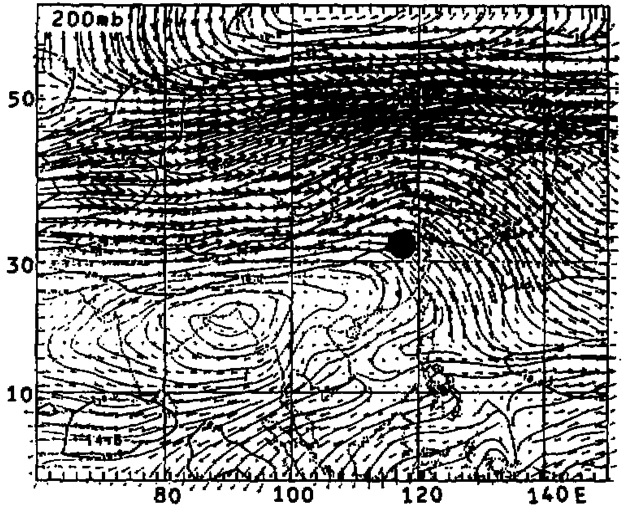


Fig. 14. 5–day mean wind field at 200 and 850 hPa for 21–25 May 1991. Black dot indicats the location of maximum cloud amount. Figure description is same as Fig. 5. a) 850 hPa; b) 200 hPa.

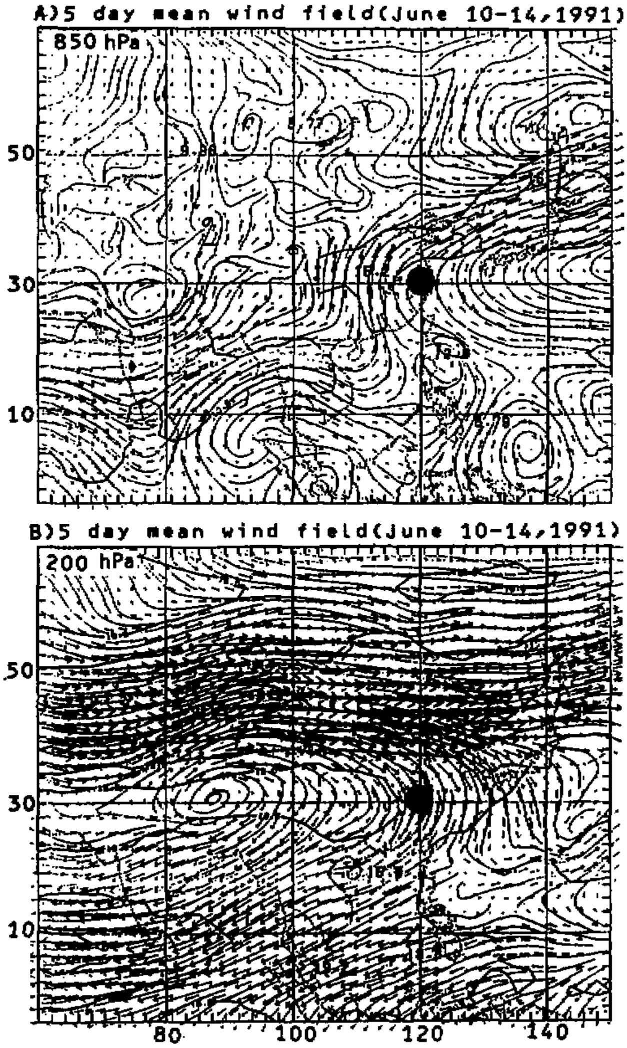


Fig. 15. Same as Fig. 14 except for 10–14 June 1991.

Fig. 14 shows the case during 21–25 May 1991, this case happened during the seasonal transition period. The frontal cloud belt was located in the area with strong SW wind at 850 hPa level and near a westerly ridge at 200 hPa level. So it was in a deep westerly region, however, the upper westerlies were weaker because they were located to south of the westerly jet. As we have known, the westerlies are associated with the baroclinic zone, so in this case, its environment was characterized by keeping some baroclinity in the upper level with significant vertical wind speed shear.

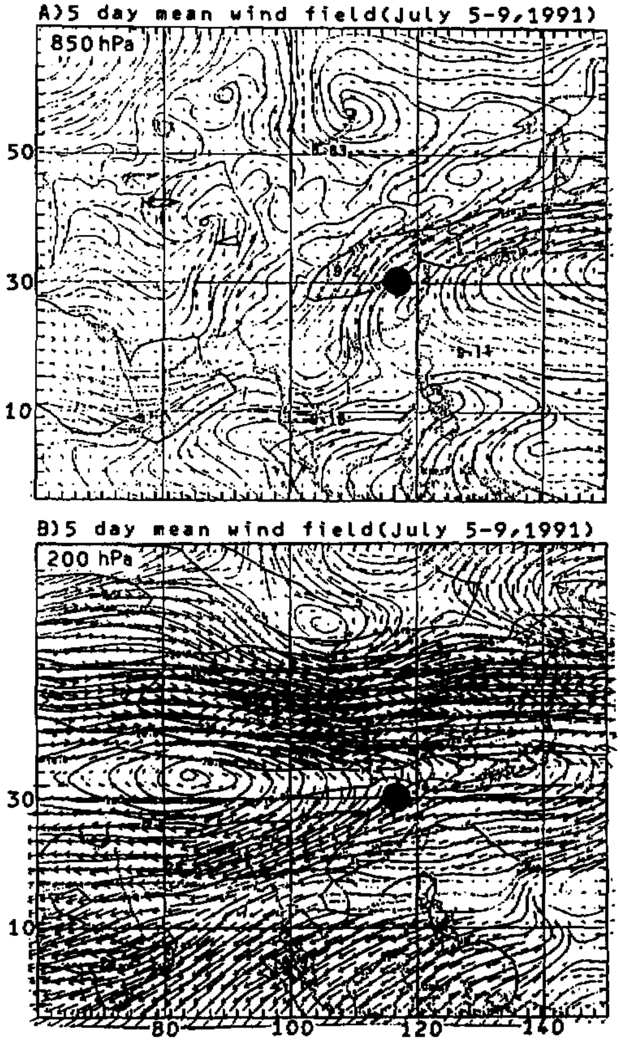


Fig. 16. Same as Fig. 14 except for 5–9 July 1991.

Fig. 15 shows the case during 10–14 June 1991, this case happened during the middle of the season. The frontal cloud belt was located to just south of the strong SW wind region at 850 hPa level and around the axis of the anticyclone at 200 hPa level, where were the very weak northerly region. As we have known that the heavy rainfall developed in the area north of the LLJ axis (Akiyama, 1973; Si, 1988b), but the upper cloud belt was located toward south of the LLJ region. We may explain this phenomenon that the upper cloud moved toward south with the upper northerlies. In this case the environment was characterized by very weak baroclinity in the mid and upper troposphere with significant vertical wind speed and direction shear.

Fig. 16 shows the case during 5–9 July 1991 which was in the late season. In this case, the frontal cloud belt was located to just south of the strong SW wind region at 850 hPa level, same situation as the 10–14 June case, and in the northeasterly region south of the anticyclone at 200 hPa level. For this case the environment was characterized by disappearance of the baroclinity in the mid and upper troposphere with rather significant vertical wind speed and direction shear.

We have shown the different environment for the frontal rainfall in the 1991 mei–yu season. The difference was displayed in the baroclinity and vertical wind shear. Research works have shown that these two factors have important influence on the development of meso–scale cloud cluster systems. Strong baroclinic environment with strong vertical wind shear is favorable for development of the severe local stroms (Newton et al., 1959). A weak baroclinic environment with significant vertical wind shear may be favorable for the development of rainstorms. Vertical wind shear has effect to maintain the convective systems and heavy rainfall (Takeda, 1965; 1966). The difference in environment in the season can have influence on the feature of heavy rainfall process. It has been indicated that the heavy rainfall during early July was more intense (Ding, 1993). Anyway, the study in the present paper is very preliminary. Many studies are needed in the furture.

VI. SUMMARY

Through investigating the early summer seasonal change of large–scale circulation and its relation to the change of frontal features and frontal rainfall environment during 1991, following conclusions have been obtained:

(1) The early summer seasonal change occurred around 20–23 May 1991, in the period the subtropical westerly jet and tropical easterlies around 120°E abruptly moved northward. This change during 1991 was about 10 days earlier than the normal which is during early June;

(2) An explosive developmant of the 100 hPa high over Southeast Asia was observed in association with the early summer seasonal change 1991. This development was before the formation of the Tibetan Plateau High. The same development was appeared in 1992 and 1993 except the period late to early June. 1990 was a different development type from 1991;

(3) During the seasonal change 1991, the tropical easterlies moved northward earlier at 100 hPa level and 24 hrs late at 200 hPa level. The phenomenon was associated with earlier disappearance of the subtropical jet at 100 hPa level;

(4) During the seasonal change 1991, there existed 2 westerly jets in the upper level and changed their intensity. Before the seasonal change, the southern one was more intense, then the northern and southern one increased and decreased their intensity, respectively, finally the southern one decreased to disappear, completed the seasonal change. This process described a concept to the subtropical westerly jet change in the seasonal transition, it was decreased to disappear.

(5) An abrupt T rising at 200 hPa level over the Tibetan Plateau appeared just before the

seasonal change 1991. Before this T rising the T maximum was over east of the plateau after the rising it moved onto the plateau. This was shown that the T rising was faster over the plateau than over its surrounding region and displayed the thermal effect of the plateau. After the change the upper T gradient to the south flank of the plateau was changed from positive to negative. This T gradient change was related to decrease and finally disappear the southern westerly jet. Also it led to the change of frontal features over East Asia, the frontal zone above 500 hPa level moved northward, separated with that in the lower level;

(6) The environment for the frontal heavy rainfall development showed some different characteristics in the 1991 mei–yu season. In late May the frontal rainfall occurred to the north of the upper anticyclone, the environment was in a deep westerly region which still kept some baroclinity in the upper level with significant vertical wind speed shear. In mid June it occurred to near the axis of the upper anticyclone, the environment was very weak baroclinity with significant vertical wind speed and direction shear. In early July it occurred to the south of the axis of the upper anticyclone, the environment was no baroclinity with rather significant wind speed and direction shear.

From this study, we have discovered many problems which need to be taken further study in future.

The authors wish to give thanks to Associate Professor Yasushi Fujiyoshi and the group of Water Cycle Section in Institute for Hydrospheric–Atmospheric Sciences, Nagoya University for their many helps.

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