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SEASONAL CHANGE
OF
ASIAN SUMMER MONSOON CIRCULATION AND ITS HEAT SOURCE

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1. INTRODUCTION

Hoskins and Rodwell (1995) show that many features of the Asian summer monsoon circulation averaged during June-August can be reproduced by a time-dependent primitive equation model with specified zonal flow, mountains, and diabatic heating. Using the model, Rodwell and Hoskins (1996) discussed about the mechanism for the northern summer dry climate in the eastern Sahara, the Mediterranean, and the Kyzylkum desert. They show that the interaction between the subtropical heat sources and the mid-latitude westerlies intensifies vertical motion in the mid-latitudes. The extended downward motion in the mid-latitudes explains the existence of dry region in the western Eurasian Continent.

The purpose of this paper is to understand the climatological seasonal change of the Asian summer monsoon circulation in a view of the model response to the prescribed heat sources (their wave components) and zonal mean fields, following Hoskins and Rodwell (1995). We studied the roles of heat sources and zonal mean fields in the seasonal change of the Asian summer monsoon circulation by exchanging zonal mean fields from one month to another and limiting the domains of the specified heat sources.

Wet climate is observed in East Asia and around Japan in the northern summer season. One of the most characteristic phenomena is the Baiu and the Meiyu (e.g., Ninomiya and Akiyama, 1992; Ding, 1992). The Baiu precipitation zone appears south of Japan in late May, then it migrates northward (Ninomiya and Murakami, 1987; Tanaka, 1992). The precipitation zone disappears around the northern Japan in mid-July.

A question is how wet climate in East Asia is simulated by the model and how it is affected by the seasonal change of zonal mean field from June to July.

Ueda et al. (1995) showed that the abrupt seasonal change occurs around late July in large-scale convective activity over the western Pacific. We are interested in whether the seasonal change of the prescribed diabatic heating reproduces the seasonal change of the Asian summer monsoon circulation from mid-summer (July) to late summer (August).

2. MODEL

The method to simulate the stationary summer monsoon circulation in this study is based on Hoskins and Rodwell (1995). The horizontal and vertical differencings of used model are based on Arakawa and Lamb (1977) and Tokioka (1978), respectively. The model has 2.52.5 grids in longitudinal and latitudinal directions. It has seven layers vertically at 0.0555..., 0.222..., 0.444.., 0.638..., 0.777..., 0.888... and 0.972.... in the modified σ-coordinate.

Integration starts from zonal mean of the monthly mean T, V and Ps, which are obtained from the initialized ECMWF reanalysis data for 1985-87. According to Hoskins and Rodwell (1995), zonal means of T, V and Ps on the sigma-levels are kept fixed to those initial condition throughout the model integration except the hydrostatic adjustments to T

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and Ps. No mountain and no land is specified south of 60°S.

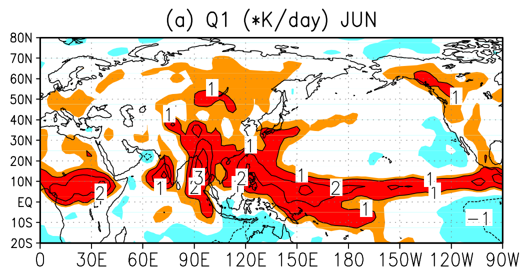
Prescribed heating rate Q1 is the monthly mean apparent heat source (Yanai et al., 1973). This is obtained by the atmospheric heat budget calculation (Hoskins et al., 1989) from every 12 hour sequences of the initialized ECMWF reanalysis data for 1985-87.

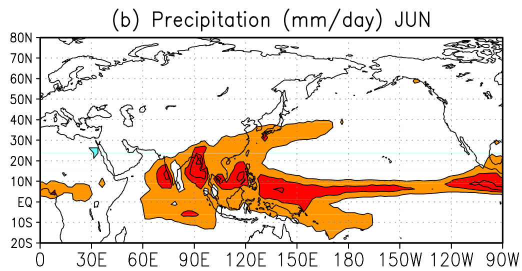
The mountains are lifted linearly with time during the first five days of integrations while the hydrostatic adjustment is made. The prescribed heat source is turned on day 5. The integration attains to the equilibrium state almost by day 10. The simulation results shown are averaged during day 11 - day 15.

3. JUNE

3.1 Heat sources and circulation

Figure 1 (a) shows the mass-weighted mean Q1 between 85 hPa and surface for June. Large and positive Q1 are found over south-east Asia. The Asian summer monsoon is characterized by convective heat sources at relatively high latitudes in the subtropics. Particularly large Q1 locates in the Bay of Bengal along 90 ° E and near the Philippines.





Precipitation due to the Baiu front (or the Meiu front) seems to expand northeastward from south-east Asia.

The climatological precipitation for June during 1979-94 is shown in Fig. 1 (b). The features of the condensational heating found in Fig. 1 (a) are confirmed in the precipitation pattern.

Figure 2 (a) and (b) show the observed streamfunction at upper-level (200 hPa) and low-level (0.78 sigma-level) for June. The vertical velocity at 500 hPa in June is shown in Fig. 2 (c). Hereafter, 200 hPa and 0.78 sigma-level are referred to as upper-level and low-level, respectively. The characteristics of the northern summer circulation are confirmed; the Tibetan High, the upper-level Pacific trough, the Indian monsoon trough, and the low-level westerly jet in South Asia. Upward motion in south-east Asia, the Baiu region, west of the Caspian Sea, around the mountains on the western edge of the Tibetan Plateau, and downward motions in the western arid regions of the Eurasian Continent are observed.

Figure 2 (d)-(f) are the same as Fig. 2 (a)-(c) except for the simulated ones. The simulations are referred to as EXP-JUN. The above observed large-scale features are well captured by the simulation. Downward motions are also simulated in the appropriate area, but those tend to be large in the magnitude as compared with the observation.

4. FROM JUNE TO JULY

4.1 Heat sources and circulation

Figure 3 (a) is the climatorological change of precipitation from June to July. We can see that precipitation over the Arabian Sea and the Bay of Bengal tend to move into inland of India. The Baiu

Fig. 1 (a) Vertically averaged diabatic heating rate (K/day) between 85 hPa and surface for June. Red, orange and blue are for more than 1.0 K/day, 0.5 K/day and less than -0.5 K/day, respectively. Contours are every 1.0 K/day. (b) Climatological precipitation rate (mm/day) from Xie and Arkin (1996). Contours are every 5 mm/day.

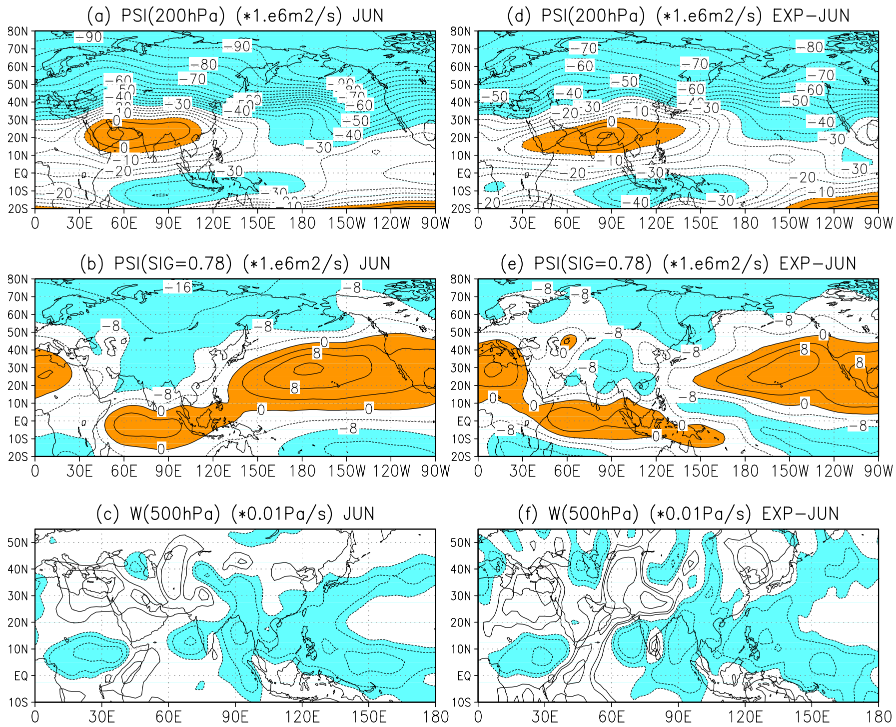


Fig. 2

Observed streamfunction (10^6 m^2/s) for June at (a) upper-level and (b) low-level.

(c) Observed vertical velocity (0.01Pa/s) at 500 hPa for June. Blue is for less than -0.02Pa/s. Contours are for -0.08 -0.04, -0.02, 0.02, 0.04, and 0.08 Pa/s.

(d)-(f) are the same as (a)-(c) except for the simulated ones (EXP-JUN).

precipitation shifts northwestward from south of Japan.

The seasonal change of zonal mean zonal wind from June to July is shown in Fig. 3 (b). Since the northern troposphere becomes warm entirely as compared with that in June, the subtropical jet moves northward and becomes weak.

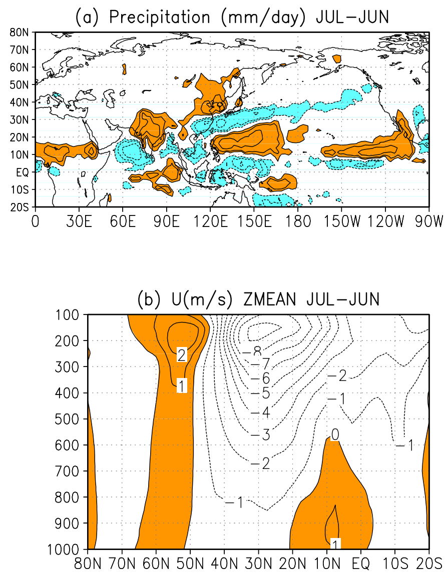


Fig.3 The differences of (a) precipitation and (b) zonal mean zonal wind between July and June. Contours in (a) are for -8.0, -4.0, -2.0, -1.0, 1.0, 2.0, 4.0, and 8.0 mm/day. Orange is for more than 1.0 mm/day, blue is for less than –1.0 mm/day.

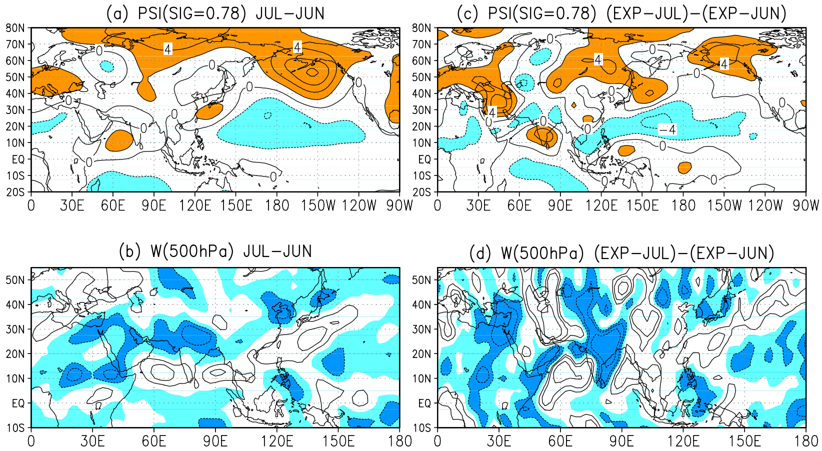


Fig. 4
The differences of (a) observed low-level streamfunction, (b) observed vertical velocityat 500 hPa between July and June. Contours are -0.04, -0.02, 0.02 and 0.04 Pa/s in (b). Blue and light blue are for less than -0.02 Pa/s and negative values (upward motions), respectively in (b). (c) (d) are the same as (a) (b) except for the simulated ones (EXP-JUL and EXP-JUN).

Figure 4 (a) and (b) show the change of the observed low-level streamfunction and vertical velocity at 500 hPa from June to July. Low-level anti-cyclonic changes are found over the Arabian Sea and over the East China Sea. Those anti-cyclonic changes mean the northward shift of low-level jet in South Asia and East Asia, respectively. Low-level cyclonic streamfunction changes are found in the northern central Pacific. Upward motion change is extended from north of the Bay of Bengal through Japan. Another one is distributed from (20 ° N, 150 ° E) northeastward. The drastic change of vertical motion in East Asia corresponds to the northwestward shift of the Baiu precipitation zone. Roughly, upward motion tends to move from the ocean side of the coasts to the continental side in East Asia and South Asia. Downward motion in the western arid region shifts its center northwestward and tends to be weak in the Middle East and the northern Africa.

The differences between the July simulation (EXP-JUL) and the June simulations (EXP-JUN) are shown in Fig. 4 (c)-(d). The details in the simulation are not necessarily well comparable to the observation. However, some characteristics in the seasonal change from June to July are simulated; low-level anti-cyclonic changes are simulated in South Asia and East Asia. Cyclonic changes are found in the subtropical Pacific. The large-scale pattern of the observed vertical motion change is roughly captured by the corresponding differences between EXP-JUL and EXP-JUN.

4.2 Effect of zonal mean field change

The differences between EXP-JUL and EXP-JUN are attributed to the seasonal changes of Q1 and zonal mean field from June to July. Figure 5 shows the differences of the simulated circulation between EXP-JULZM and EXP-JUN. The July zonal mean field and the June Q1 on the globe are used in EXP-JULZM. The result (Fig. 5a) is interesting since the model response to the July zonal mean field seems to capture some qualitative characteristics of the monsoon circulation change from EXP-JUN to EXP-JUL (Fig. 4c); low-level anti-cyclonic changes are found along the coasts in East Asia and South Asia so that low-level jets tend to flow inside of the Continent. The characteristic low-level jets in June both over South Asia and on the southeastern side of the Baiu precipitation are weakened.

The differences of vertical motion between EXP-JUL and EXP-JUN (Fig. 4d) are quite similar to those between EXP-JULZM and EXP-JUN (Fig. 5b). We can confirm that the qualitatively similar pattern is

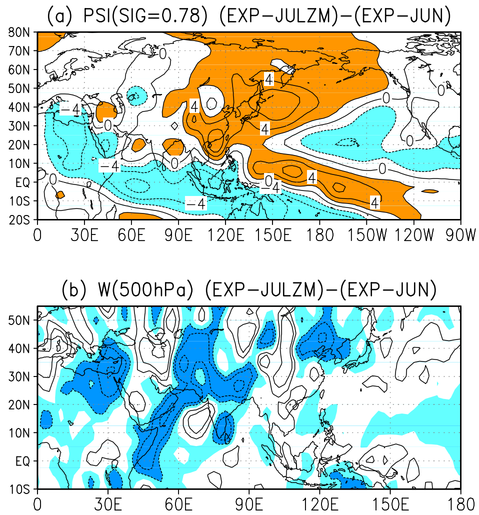


Fig.5 (a) and (b) are the same as Fig. 4 (c) and (d) except for the differences between EXP-JULZM (the zonal mean field in July and the heat sources in June) and EXP-JUN.

also found in the observed seasonal change from June to July (Fig. 4b).

It is an interest that the change of precipitation and vertical motion from June to July do not contradict with the changes only due to the zonal mean field. This fact indicates that the convective activities distribute consistently with zonal mean fields in the climatological seasonal change.

The seasonal changes of vertical motion or precipitation are understood to some extent by considering the interaction of zonal mean field change with the mid-latitude circulations induced by the convective precipitation in South Asia and Southeast Asia.

5. FROM JULY TO AUGUST

5.1 Heat sources and circulation

Figure 6 show (a) the change of climatorological precipitation from July to August. The most drastic change is found over the subtropical western North Pacific. Increased precipitation is extended from the Philippines eastward to the dateline over the western Pacific.

According to Murakami and Matsumoto (1994) and Ueda and Yasunari (1996), the western warm SST and the associated SST gradient are basically responsible for the occurrence of deep convection over the western Pacific in late summer at least in a climatological sense.

The climatorological change of zonal mean zonal wind from July to August is shown in Fig. 6 (b). The seasonal change of the zonal mean zonal wind is small as compared with that from June to July (Fig. 3b), especially in the mid-latitudes.

Figure 7 (a)(b) show the change of the observed upper-level streamfunction and low-level streamfunction from July to August. Low-level heat lows over the Eurasian Continent are entirely weakened. Low-level westerly jet in South Asia shifts

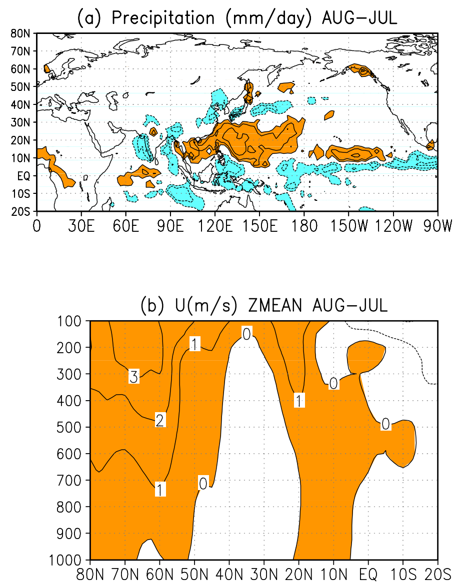


Fig. 6 The same as Fig. 3 except for August and July.

southward.

The Tibetan High seems to shrink from the northwestern area of the Continent and expand to over Japan. Low-level westerly jet in South Asia tends to invade the western Pacific. Anti-cyclonic circulation prevails over Japan in upper- and low-levels.

Figure 7 (c)(d) are the same as Fig. 7 (a)(b) except for the simulated ones. The August simulation is referred to as EXP-AUG. Major features for the Asian summer monsoon in August are obtained. The seasonal change of circulation over Japan have a barotropic structure of anti-cyclonic circulations as observed.

5.2 Effect of the western Pacific heat source

Two regional parts of the August Q1 are considered separately. The two regions are referred to as the western Pacific (WP) region and the Indian Ocean and Eurasian Continent (EU) region, respectively (see the definition in Ose, 1998). The EXP-WP case is the same as EXP-JUL except that the Q1 in July over the WP region is replaced by that of August. The EXP-EU case is also the same as EXP-JUL except that the Q1 in July over the EU region is replaced by that of August. Zonal mean field is fixed to the July one in both cases.

Figure 8 shows the differences between EXP-WP and EXP-JUL in (a) the upper-level streamfunction and (b) the low-level streamfunction. The upper-level streamfunction in EXP-WP captures its major changes from EXP-JUL to EXP-AUG over the Pacific and even over the Indian Ocean. The organized heating over the WP region is responsible for that circulation response. Low-level circulation response tends to be inverse to upper-level response in the tropical and subtropical regions. The response in the mid-latitudes including Japan is barotropic rather than baroclinic. The seasonal change of zonal mean component is not negligible for the low-level differences in high latitudes.

Cyclonic circulation anomalies over the Eurasian Continent and a part of anti-cyclonic anomalies over Japan are simulated for the EXP-EU (not shown here, see Ose, 1998). The simulated low-level circulation in EXP-EU is limited around South Asia and is consistent with the southward shift of the South Asia monsoon flow.

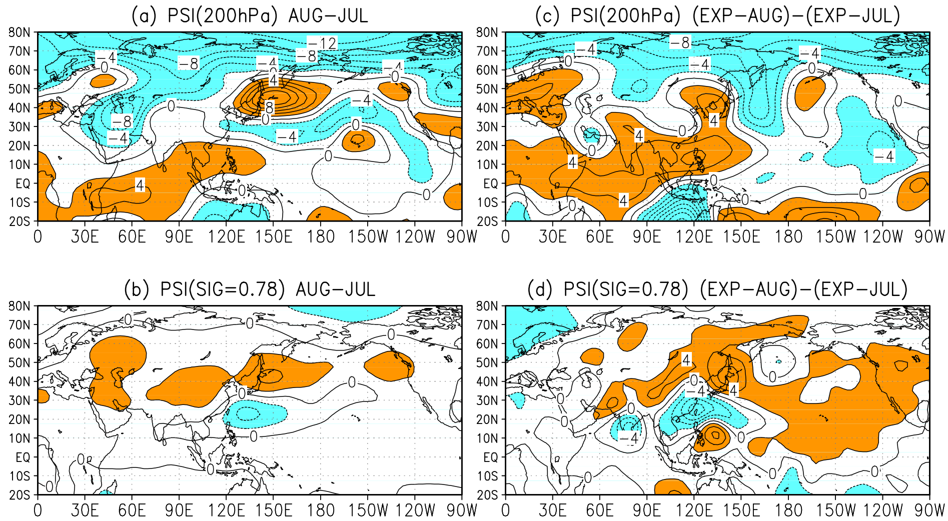


Fig. 7 The same as Fig. 4 except for EXP-AUG and EXP-JUL.

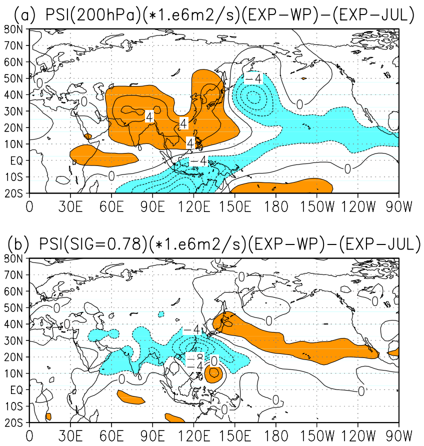


Fig. 8 (a) and (b) are the same as Fig. 5 (a) and (b) except for the differences between EXP-WP (the same as EXP-JUL except that the heat sources only over the western Pacific are replaced by those in August) and EXP-JUL.

6. SUMMARY

The roles of heat sources and zonal mean fields in the seasonal change of the Asian summer monsoon circulation are studied with a type of the model of Hoskins and Rodwell (1995) by exchanging heat sources and zonal mean fields from one month to another.

Seasonal change from early summer (June) to mid-summer (July) is characterized by air temperature increase in the whole Northern Hemisphere and northward shift of weakened westerly jet. The change of zonal mean field from June to July in the model explains the major characteristics of the climatological seasonal change from June to July; low-level jets and upward motion areas in South Asia and East Asia shift from the ocean side to the land side of the coasts.

The vertical motion change due to the zonal mean field change is consistent with that due to the seasonal change of the heat sources from early summer (June) to mid-summer (July).

Seasonal change from mid-summer (July) to late summer (August) is characterized by enhanced convective activity in the extended area of the subtropical western Pacific. The change of the heat source over the western Pacific solely explains the major characteristics of the climatological seasonal change from July to August not only over the Pacific but also over the Indian Ocean. The expansion of the Tibetan High at upper-level and the Pacific High at low-level over Japan is also simulated only by the seasonal change of the western Pacific heat sources.

Acknowledgments

The figures are made with use of the GrADS (the Grid Analysis and Display System) provided by the COLA (Center for Ocean-Land-Atmosphere Studies).

A part of this study is made in the Japanese Experiment on Asian Monsoon or JEXAM (1989-1998) supported by the Japan Science and Technology Agency.

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