The break in Mongolian rainy season and its possible mechanism

Hiroyuki IWASAKI and Tomomi NII

Faculty of Education, Gunma University, 371-8510, Japan

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1. Introduction

Iwasaki and Nii (2005) found that there is a break in a Mongolian rainy season in the middle of July, which had not been reported till now. The purpose of this paper is to investigate interannual variation of the break in Mongolian rainy season and to discuss its possible mechanism.

2. Data

Data used in the present analysis are surface a meteorological data set provided by IMH, Mongolia, sonde data at Ulannbaator (UB) and NCEP/NCAR reanalysis data. The surface meteorological data set contains 3-hourly air temperature, 3-hourly relative humidity, and twice-daily precipitation values from 1993 to 2001 for 97 stations.

3. Break in the Mongolian rainy season

a. Seasonal change of rain and water vapor

Figure 1 shows typical seasonal variation of mean 10-day rainfall at Bayanchandanima (BC) near UB with high annual precipitation in the forest steppe vegetation zone and Khanbogd (KB) with low annual precipitation in the desert vegetation zone. Averaged period of BC and KB are 8 and 9 years, respectively. 8-year mean 10-day rainfall at BC in Fig. 1a reaches a maximun in the beginning of July, decreases to 1/3 the first maximum value in the middle of July (break), and recovers in the beginning of August. The rainfall at KB in the desert also has a clear break. The break is unrelated to the difference in annual precipitation

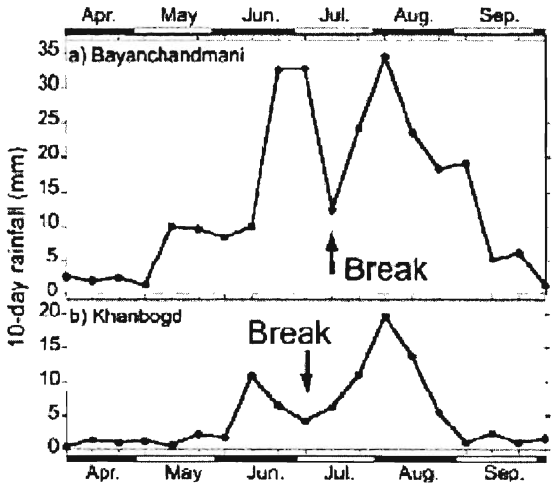

Figure 1: Time series of mean 10-day rainfall at BC (a) and KB (b). The arrows indicates the "break" in the rainy season.

Even though a very clear break is recognized as shown in Fig. 1, water vapor at the surface reached a maximum in the middle of July at both stations, and there are no apparent minimun uring the break period (not shown). Figure 2 shows the time series of 31-year mean precipitable water (PW) and Showalter stability index (SSI) at UB located 35 km to the southeast of BC. In order to eliminate the affect of diurnal variation, upper sounding data at 8 MST (0 UT) were used.

In addition to water vapor at the surface, 31-year mean PW also reaches a maximum and 31-year mean SSI reaches a minimum in the middle of July (Fig. 2a and 2b). The mixing ratio of water vapor at the surface, PW, and SSI for the each break year fluctuated from their mean value, however, their variation do not always correspond to the break period. The maxima of water vapor and the latent instability are frequently recognized even in a break year. Thus, the break period in the Mongolian rainy season still has moisture air with large latent instability.

Seasonal change of mean temperature lapse rate from 850 to 500 hPa is shown in Fig. 2c. It should be noted that the mean lapse rate in July is larger by 0.5-1.0 K than in June and August, indicating that latent instability (minimum of SSI) in the break period is caused by high mixing ratio of water vapor values in lower atmosphere, and a stratification in the break period is rather stable. This increase in the lapse rate in July substantially attributes to higher temperatures at 500 hPa (not shown).

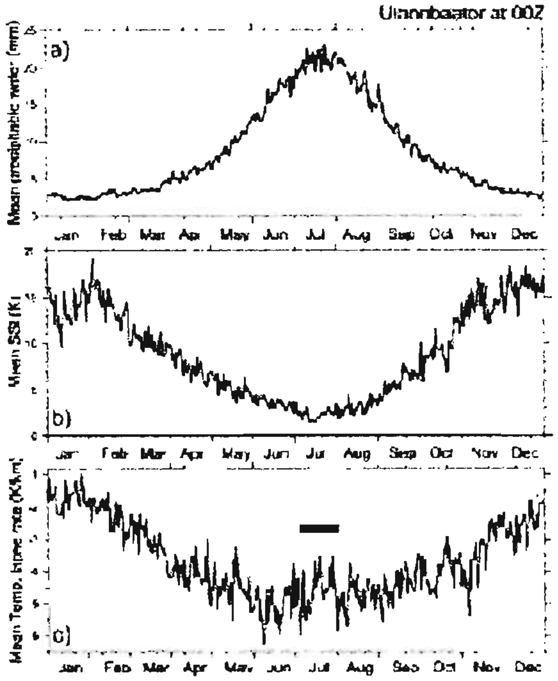

Figure 2: Seasonal change of mean daily precipitable water (a), mean daily Showalter stability index (b) and mean daily temperature lapse rate from 850 to 500hPa c) at Ulaanbaator (1306 m ASL). Upper air sounding data at 8 MST (=0 UT) from 1973-2004 were used.

b. Interannual variation of the break in the rainy season

Since it is well known that interannual variation of rainfall in Mongolia is large, the break did not always occur. Figure 3 shows the seasonal change of 10-day rainfall for each year averaged in stations located west and east of 100oE. The property of the break is summarized in Table 1. However, the averaged rainfall is heavily weighted by the stations with high annual precipitation. In order to classify the years with and without the break, the seasonal variation of rainfall in the arid and semi-arid region is also considered. In the results, five years (1994, 1996, 1999, 2000 and 2001) are classified as the year with the break (break years), and the others are the year without the break (non-break years).

Table 1: Properties of the break in each rainy season

1993	N	C	N	-
1994	C	V	CV	CIn phase
1995	N	N	C	Out of phase
1996	RC	CR	C	In phase
1997	N	N	VC	Out of phase
1998	N	N	N	-
1999	C	VC	C	In phase
2000	RC	C	VC	10 days late
2001	RC	C	N	-

Existence of the break for western and eastern Mongolia and the stationary Rossby wave are described in four categories (VC: Very clear, C: Clear, RC: Rather clear, N: Not clear).

Year Existence of break The stationary Rossby wave around 85-110E in July West East Existence of Rossby wave Phase

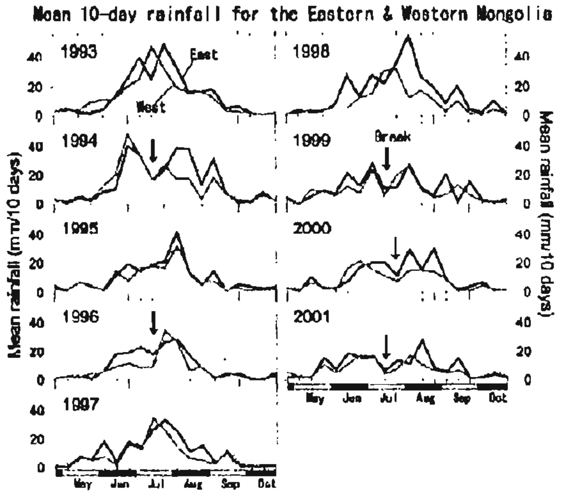

Figure 3: Seasonal change of mean 10-day rainfall for western and eastern Mongolia. Gray line and black line indicate rainfall of western and eastern Mongolia, respectively. Arrows indicate the break period for each year.

There are three characteristic years. The break in 1994 had the strongest signal 9 year period over all of Mongolia. Although the break in 2000 was also lear, the minimum of rainfall was observed in the nd of July; it was 10 days later when compared with the climatological mean. In 1997 (a non-break year) a lot of rainfall was observed in the middle of July over both western and eastern Mongolia. These three years will be discussed from the point of view of the possible mechanism of the break in the next section.

4. A possible mechanism of the break in the Mongolian rainy season

a. Development of a ridge at 500 hPa in the break period

The increase of the temperature lapse rate in the middle of July in Fig. 2c suggests the development of a ridge over Mongolia. Here, the from 20-140oE along 45oN, and a weak ridge exists over Mongolia.

This wave pattern can be seen more clearly in the difference of mean Z500 in the break years and mean Z500 in the non-break years for the middle of July (Fig. 4b). Differences in geopotential height associated with the ridge R1 and trough T1 are extremely large because a weak trough and a weak ridge exist to the east of the Black Sea and the Caspian Sea in the non-break year, respectively. Westerly circulation in the break years over the Eurasian Continent is quite different with that in the non-break years. Thus, these figures do indicate that a ridge R2 develops over Mongolia in the break year. relationship between the development of a ridge and the break in rainy season will be described. Figure 4a shows a composite map of geopotential height at 500 hPa (Z500) for the middle of July in the break years. A wave pattern is predominant

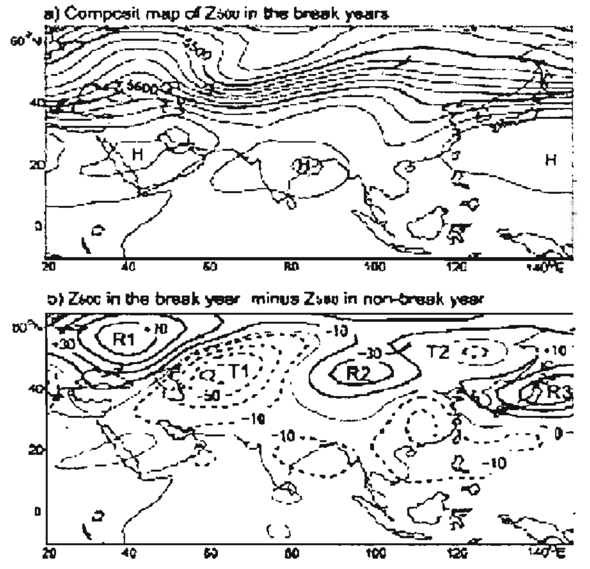

Figure 4: a) Composite 500 hPa height map for the middle of July (11-20 July) in the break years. b) Difference of 500 hPa height between the break years and non-break years for the middle of July (break years minus non-break years)

b. The stationary Rossby wave as a possible mechanism

Terao (1998 and 1999) showed that the stationary Rossby waves trapped in the subtropical jet predominated over the Eurasian Continent during summer through statistical and model analysis. The dominant mode of the Rossby waves is characterized by barotropic structure, a time scale of 40 days and a wave length of 50 degrees in longitude (wave number is 7). Furthermore, the Rossby wave train is phase-locked in the zonal direction. Both the wave length and the phase-locked feature are similar to those of Fig. 4 in the present study. The stationary Rossby wave trapped in the winter Asian jet had been discussed using a theoretical model by Hoskins and Ambrizzi (1993). Ambrizzi and Hoskins (1995) showed the Rossby wave activity can propagate along the Asian jet even in the summer, and although the summer waveguide for the stationary Rossby wave was weaker it shifted northward and extended more eastward than in the winter.

Teleconnection over the Eurasian continent in the summer season reported by Krishnamand and Sugi (2001) have a similar features to the propagation of the stationary Rossby wave. Recently, Enomoto et al. (2003 and 2004) extended this theory to the formation mechanism of the Bonin high and interannual variation of the Baiu-front activity. We also adopt this theory to interpret the mechanism of the break in Mongolian rainy season. Through a band-pass filtered meridional wind velocity analysis in the manner of Terao (1998), the possible mechanism of the break in the Mongolian rainy season will be discussed.

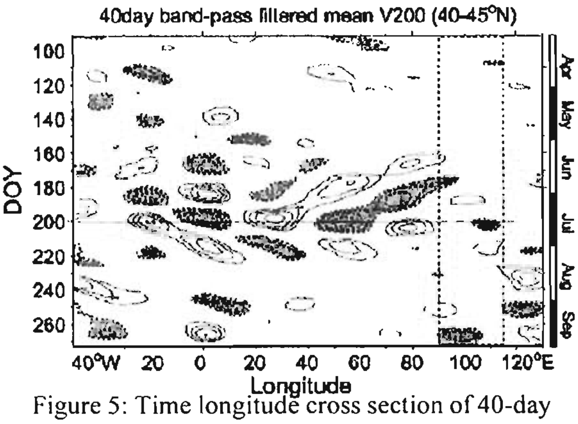

Figure 5: Time longitude cross section of 40-day band-pass filtered 23-year mean meridional wind speed at 200 hPa along the climatic Asian jet (40-45oE). Contours are every 0.5 m/sec, but values from -1 m/s to 1 m/s are not plotted. Negative areas less than -1 m/s are shaded. Vertical dashed lines indicate the location of Mongolia and the horizontal line is 200 in DOY (18 July)

Figure 5 shows a time longitude cross section of mean meridional wind speed at 200 hPa along the climatic Asian jet (40-45oN) calculated from NCEP/NCAR reanalysis data from 1979 to 2001. A 40-day band-pass filtered (half amplitude periods are 25-day and 60-day) was applied for the meridional wind so as to extract the dominant mode of the stationary Rossby wave pointed out by Terao (1998 and 1999). The stationary Rossby wave can be seen clearly from 180 to 225 in DOY (from 28 July to 15 August) and extends eastward to westernmost Mongolia (90oE). The origin of the wave train is near 30oW far from the entrance region of the Asian jet, which is consistent with Terao (1998 and 1999). These features are also well recognized from 35 to 50oN, implying the enhancement of the stationary Rossby wave in July was not attributed to northward propagation of the Asian jet, but to the seasonal evolution of the Rossby wave train itself. It is noted that the Rossby wave trains are phase locked not only in the zonal direction, but in seasonal evolution as well, and the amplitude of mean meridional wind speed reaches a maximum around 200 in DOY (18 July). This period corresponds to the break in Mongolian rainy season, and weak northerly and southerly wind can be seen even in 23-year mean data around 80oE and 110oE, respectively, indicating the existence of a weak ridge over Mongolia.

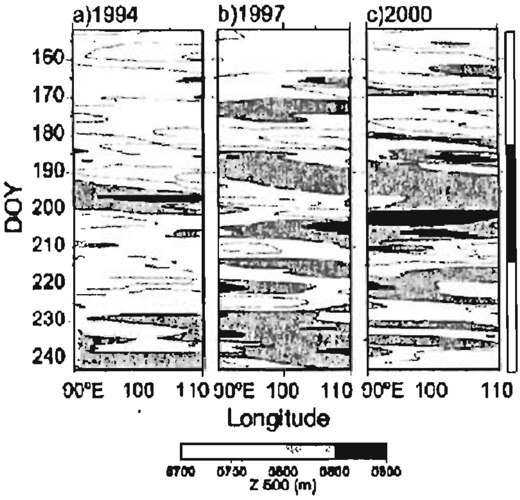

Figure 6: Time-longitude cross section of geoptential height at 500 hPa averaged from 45 to 50oN over Mongolia. Contours are every 50 m and the dashed ine is 5700 m

The relationship between interannual variation of the break and the stationary Rossby wave will be examined for three years (1994, 1997, and 2000). A distinct break was found in 1994 as shown in Fig. 3. Figure 6 shows the time-longitude cross section of Z500 over Mongolia for these 3 years. The ridge was developed at 500 hPa over Mongolia during the break period of the middle of July. This ridge corresponds to R2 in Fig. 4b. The development of the ridge is consistent with the increase of the temperature lapse rate in Fig. 2c, and convective clouds would be suppressed under the developed ridge. Figure 7 shows the time-longitude cross section of 40-day band-pass filtered meridional wind speed at 200 hPa along the climatological Asian jet. The stationary wave trains are predominant until 200 in DOY, and they are in phase with the climatological mean in Fig. 5. There are considerable southerly and northerly components around 80oE and 110oE, respectively in the middle of July, implying that the ridge was developed at 200 hPa over Mongolia. The distinct break in 1994 and developed ridge at 500 hPa were coincident with the development of the ridge at 200 hPa due to the stationary Rossby wave. Because of the barotopic structure of the stationary Rossby wave (Terao 1998 and 1999), a ridge at 500 hPa should be considered as a part of the stationary Rossby wave.

The break in 2000 was observed in the end of July, which is 10 days later than the climatological mean (Fig. 3). The phase of the ridge at 500 hPa and the stationary Rossby wave at 200 hPa were also late for 10-day than climatological mean (Fig. 6c and Fig. 7c). The break period in 2000 also synchronized with the stationary Rossby wave.

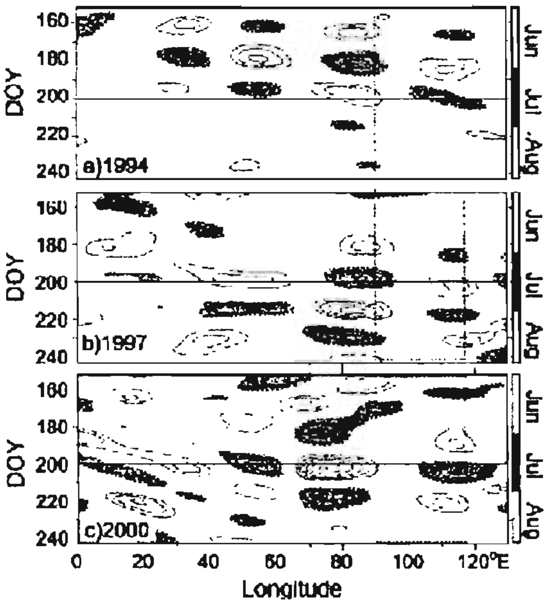

Figure 7: Time-longitude cross section of 40-day band-pass filtered meridional wind speed averaged from 40 to 45oN at 200hPa. Contours are every 2.5 m/sec, but values from -2.5 m/s to 2.5 m/s are not plotted. Negative areas less than -5 m/s are shaded. Vertical dashed lines indicate the location of Mongolia and horizontal lines are 200 in DOY (18 July).

As for the middle of July in 1997, the break was only not observed, but 10-day rainfall reached maximum (Fig. 3) and a trough prevailed at 500 hPa over Mongolia (Fig. 6b). Although the stationary Rossby wave and wave trains were clear rom July to August (Fig. 7b), they are out-of phase in comparison with the climatological mean. The precipitation in the middle of July in 1997 was also coincident with the development of trough at 200 hPa due to the stationary Rossby wave.

These facts indicate that the break in the Mongolian rainy season is caused by the stationary Rossby wave trapped in the Asian jet, and the interannual variation of the break is also caused by variation of the stationary Rossby wave. Since the stationary Rossby wave was climatologically phase-locked in seasonal evolution and the mean amplitude reached a maximum around the middle of July as shown in Fig. 5, the break period was also concentrated around the middle of July.

On the other hand, the anomalous high R2 at 500 hPa does not spread to the easternmost area of Mongolian in the break year as shown in Fig. 4b, which is a contradiction to the result that break is apparent over eastern Mongolia (Iwasaki and Nii 2005). According to Terao (1998), although the Rossby wave has a barotropic structure, the vertical structure, extracted using 40-day band pass filter, exhibits westward phase tilt toward the upper evels, and the phase difference between 500 hPa and 850 hPa is up to 6 degrees of longitude. That is, the ridge in the lower troposphere should be located about 500 km to the east of the ridge at 500 hPa. The vertical structure of the Rossby wave is one possible mechanism to solve the contradiction.

5. Summary

Seasonal and interannual variation of rainfall over Mongolia was analyzed using 9-year twice daily rainfall data and NCEP/NCAR reanalysis data. 9-year mean rainfall decreased in the middle of July, even though the middle of July has air with a high moisture content and latent instability according to upper air soundings at Ulaanbaator. We called this period "the break in the Mongolian rainy season.

" The break in the rainy season was not observed every year. Clear breaks were recognized in 5 years among the analysis period of 9 years. In 5 year with the break periods, the stationary Rossby waves trapped in the Asian jet were predominant at 200 hPa and a barotropic ridge associated with the stationary Rossby wave developed over Mongolia. These conditions suppressed deep convection even in the moist environment with latent instability. Furthermore, interannual variation of the break was also corresponded to the variation of the stationary Rossby wave. Thus, it is concluded that the break of Mongolian rainy season results from the stationary Rossby wave trapped in the Asian jet. The stationary Rossby wave was climatologically phase-locked in seasonal evolution and the mean amplitude reached a maximum around the middle of July, as the result, the timing of the break in Mongolian rainy season was also concentrated around the middle of July.

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