Air Quality, Atmosphere & Health (2019) 12:197–215
https://doi.org/10.1007/s11869-018-00658-5

Observations on changes in Korean Changma rain associated with climate warming in 2017 and 2018

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Received: 21 September 2018 / Accepted: 7 December 2018 / Published online: 12 January 2019
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Abstract

The period of prolonged summer rain in Korea called Changma was studied. Changma, also known as Meiyu in China and Baiu in Japan, is an integral part of the East Asian Summer Monsoon System. Until the 1980s, the Changma rainy season in Korea occurred from late June and July for 30 to 40 days or approximately 4 to 5 weeks. This study investigated whether changes have been observed in the timing and amounts of precipitation associated with Changma. From the analysis of meteorological data obtained in 2017 and 2018, it is observed that the length of the rainy season has shortened to 2 to 3 weeks in agreement with the earlier studies. Furthermore, during the rainy season, there were many days of no rain and partly cloudy days. Although an active elongated-linear Changma front was common in the past, it was found that an inactive Changma front with a large meridional amplitude has caused intermittent rain showers for several hours from linear convective cloud streaks. In recent years, this has produced large variations in rainfall amounts among regional measuring stations in Korea. Climate warming in the north side of the Changma front has resulted in less contrast with the warm-moist air in the south side of it from the Pacific Ocean. This has resulted in a weaker and inactive quasi-stationary front which has caused a discontinuous broken Changma front and sporadic showery days. It is also observed that maritime polar air mass, mP, over the Okhotsk Sea of far eastern Russia has not affected the Changma front over the Korean Peninsula. Overall, this study found that the characteristics of past Changma fronts have changed significantly in recent years. The present observations imply the need of further studies on climate change and summer rainfall including water management.

Keywords Changes of Changma rain in Korea · Shortened Changma season with climate change · Changma-Meiyu-Baiu rain · Torrential rain showers with a Changma front · Regional bias in summer rainfall amounts

Introduction

The air, water, and soil are critical elements for the hydrological cycle, living organisms, and the human-environment system. These elements determine the welfare and sustainability of the ecosystem and humans around the world. Adequate availability of water and precipitation is necessary for healthy living and natural abundance. By way of example, the Korean Peninsula (Fig. S1) annually receives approximately 826 to 2007 mm (KMA 2012) of precipitation, and about one half of this annual rainfall occurs in the summer rainy season, or one quarter in Changma, as shown in Fig. 1. Most of the rainwater is required for general daily household use as well as agriculture and manufacturing, etc.

This regional phenomenon of summer rain is known as "Changma rain" in Korea, while it is called "Meiyu" in China and "Baiu" in Japan. Changma rain usually occurs with the quasi-stationary polar front which forms between the cool-dry polar air in the East Asian continent, continental polar (cP) and the warm-moist maritime tropical air, maritime tropical (mT) from the northwest Pacific Ocean.

It was found that the general characteristics associated with the Changma* (Meiyu/Baiu) rainy season were:

a. Formation of W-E oriented linear quasi-stationary polar front.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11869-018-00658-5) contains supplementary material, which is available to authorized users.

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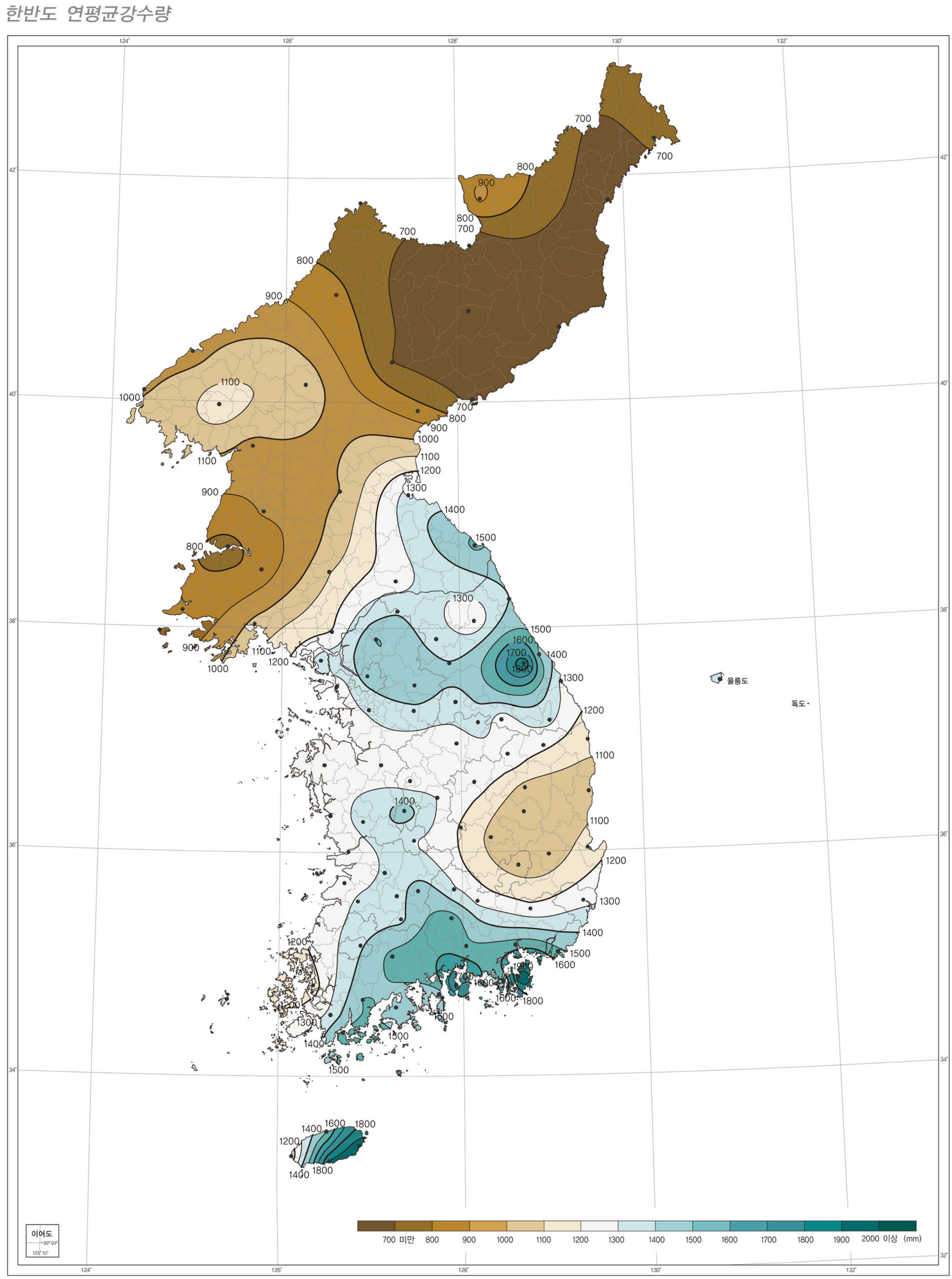

Fig. 1 **a** Distribution of annual precipitation amounts in the Korean Peninsula (KMA 2012). **b** Variations of precipitation amounts observed in south Korea during 1960~2010

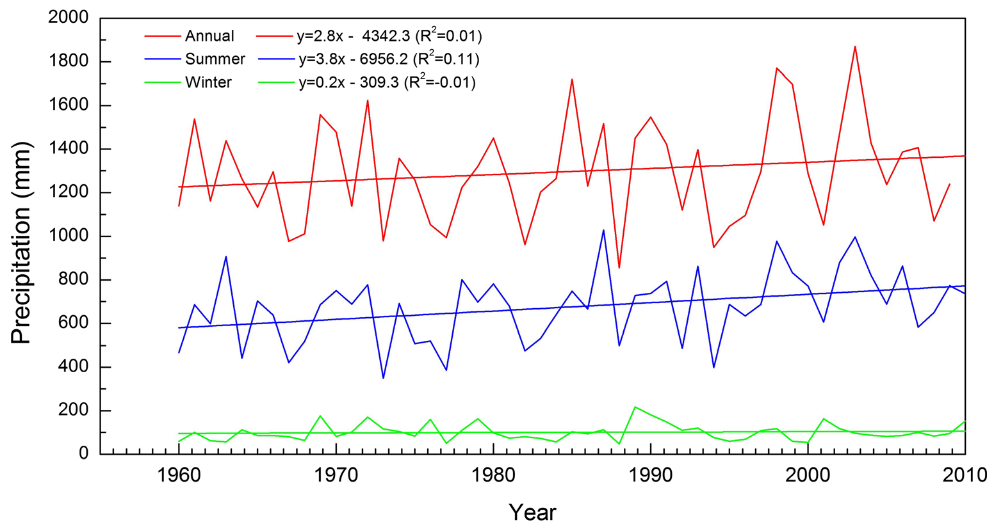

Fig. 1 (continued)

b. Gradual propagation of the Changma front northward from mid-June to early July.
c. Steady rainfall for about 30 to 40 days in June and July.
d. Relatively few days of sunny and partly sunny skies without rainfall.
e. Formation of mold and fungus inside buildings.

In recent years, it was observed that the above phenomenon and features were not regularly occurring in the three East Asian countries of Korea, China, and Japan. Clearly, the rainy

Table 1 Comparison of observed rainfall amounts (mm) of May–June–July in 2017 with the average data of same months in 1981~2010

Station	May	Normal	June	Normal	July	Normal	July differ	July ± %
Seoul	16.1	105.9	66.6	133.2	621.0	394.7	226.3	57
Inchon	21.6	100.3	49.3	112.0	478.3	319.6	158.7	50
Suwon	22.5	97.8	27.6	129.2	684.5	351.1	333.4	95
Chunchon	25.5	104.0	38.1	123.1	477.8	383.8	94.0	24
Kangreung	25.2	87.0	26.0	120.6	243.6	242.8	0.8	0
Uleungdo	24.5	105.1	37.4	115.3	86.2	170.2	− 84.0	− 49
Cheongju	11.9	88.3	17.5	144.1	789.1	282.7	506.4	179
Daejon	29.3	103.7	35.3	206.3	434.5	333.9	100.6	30
Seosan	27.9	105.2	23.3	138.4	327.8	273.4	54.4	20
Cheonju	51.5	91.5	100.0	167.9	216.4	299.6	− 83.2	− 28
Kwangju	30.2	96.6	42.1	181.5	211.6	308.9	− 97.3	− 31
Heuksan	21.9	102.4	26.1	174.7	110.6	226.0	− 115.4	− 51
Yeosu	49.5	146.5	81.6	213.7	113.5	291.5	− 178.0	− 61
Mokpo	14.0	89.2	28.5	173.1	138.2	236.7	− 98.5	− 42
Daegu	33.1	80.0	71.5	142.6	105.3	224.0	− 118.7	− 53
Ahndong	22.0	91.5	24.0	136.8	454.4	244.3	210.1	86
Pohang	19.8	85.2	12.8	141.6	74.2	203.2	− 129.0	− 63
Busan	39.2	157.4	49.8	206.7	172.1	316.9	− 144.8	− 46
Ulsan	26.3	108.1	38.5	176.8	104.6	232.3	− 127.7	− 55
Changwon	31.1	142.2	58.7	232.3	162.4	293.8	− 131.4	− 45
Cheju	38.5	96.4	60.7	181.4	35.2	239.9	− 204.7	− 85
Seoguipo	59.2	205.8	247.4	276.9	51.8	309.8	− 258.0	− 83
Mean	29.1	108.6	52.9	164.9	277.0	280.9	− 3.9	− 1.4
Difference	− 79.5		− 112.1		− 3.9			
%	27		32		99			

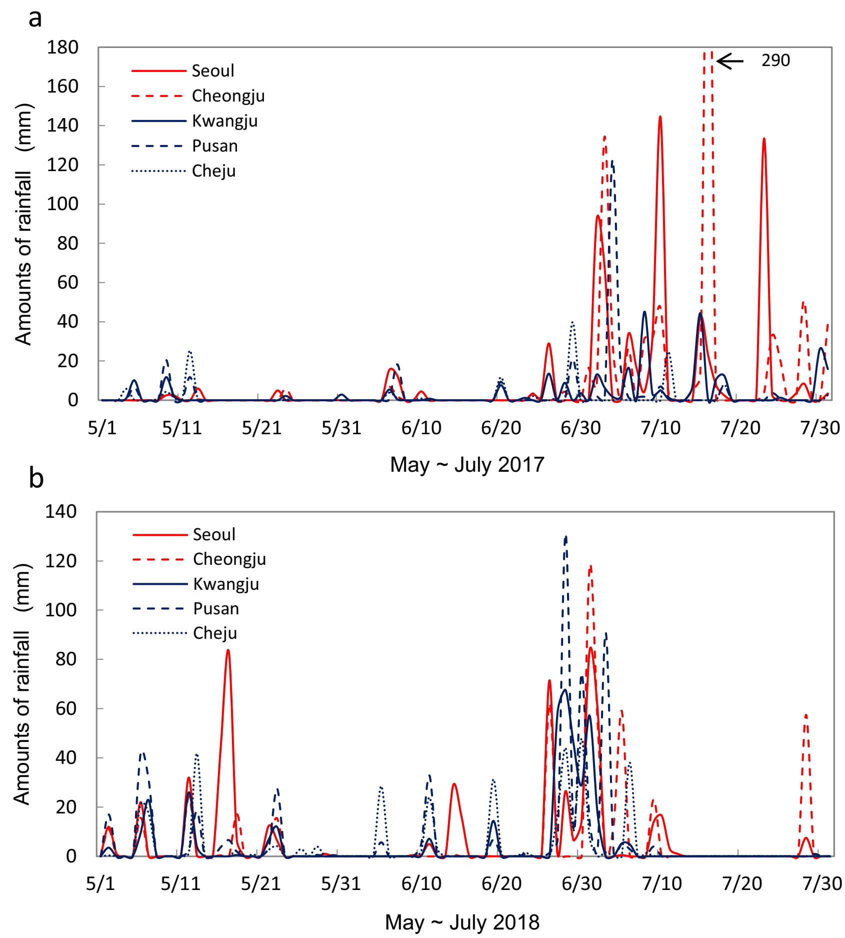

Fig. 2 Variations of daily rainfall amounts from May to July in 2017 (**a**) and in 2018 (**b**)

season has changed in recent decades. These changes in Changma have been associated with climate change as reported by Chung and Yoon (2000).

Changma rain is considered if prolonged rain, or rain showers occur for 5 days in a week and this should be developed for at least 2 weeks at each station in summer season. With a quasi-stationary Changma front, a rainfall amount in each day exceeding 5 mm is included in the present study.

This study investigated the Changma characteristics that manifested in 2017 and 2018. Observations were made of the heavy rainfall and showery convective activity in the summer rainy season. The change in the number of rainy days and showery cloud streaks were found to be important factors in a series of studies (Chung and Yoon 1999, 2000; Chung et al. 2004). In addition, the occurrence of drought is included to support the observation of the changes in the Changma phenomena[1].

Observations of Changma season and rainfall in 2017

During the last 3 to 4 years, relatively dry seasons have been recorded in Korea. The winter of 2016 was dry with a lack of snowfall, and in 2017, there were prolonged dry days in Korea from April to May. Much of Korea's vegetation including farmed fruit trees were recorded as drying and dying. Table 1 shows the average monthly rainfall, as well as the monthly rainfall, observed in May, June, and July of 2017, as observed by the Korea Meteorological Administration (KMA). Note that a comparison of average yearly and average monthly rainfall in May and June in 2017 were only 27% of and 32% of the average years of 1981 to 2010 (KMA 2012), respectively. There was so little rainfall that the spring drought continued into June. However, rainfall amounts in central Korea increased significantly in July of 2017. They averaged more than the monthly rainfall amounts of July between 1981 and 2010. On the other hand, monthly rainfall amounts of July 2017 in southern Korea were much less than the amounts recorded in July from 1981 to 2010.

[1] Changma is originated from the Korean words for "prolonged rainy period" in summer. Meiyu in Chinese and Baiu in Japanese both mean "plum rain," indicating a rainy season with ripening plums. The terms Meiyu and Baiu also seem to have originated from the Chinese character for mold, an unpleasant environment of persistent warm, damp and rainy conditions.

Figure 1a shows the annual rainfall amounts for Korea. It indicates that there were more rainfall amounts in southern Korea, while central Korea received slightly less rainfall each year. Conversely, the amounts of rainfall in 2017 were not standard. This irregularity resulted from the Changma rainfall, as shown in Table 1.

Figure 1b illustrates the variation in monthly rainfall amounts in Korea from 1960 to 2010 (KMA 2012). Winter precipitation amounts were less than 150 mm. The rainfall amounts from June to August in summer equal about one half of the annual precipitation amounts. Importantly, annual precipitation amounts have increased steadily during the last 50 years, and, with climate change, annual precipitation amounts during the last 100 years have increased about 260 mm (Chung et al. 2004).

In general, Changma rain runs from the second to the third part of June each year. A prolonged drought occurred during May and June 2017. However, the showery days from July 1 to July 4 began with over 134.4 mm in Cheongju and Ahndong. From July 6 and July 11, heavy rain showers occurred in Seoul and its surrounding urban areas. These events marked the beginning of the Changma rain in central Korea, while the Changma in southern Korea started a week later. Climatologically, Changma should have initiated from Cheju Island in southern Korea when a quasi-stationary Changma front moved northward from Okinawa and Kyushu, Japan.

Monthly July rainfall amounts from 1981 to 2010 were 280.9 mm, while the amount was 277.0 mm in July 2017 (Table 1). In fact, the July 2017 rainfall amounts in the north of Daejeon and Seosan in central Korea were 20 to 179% larger than the monthly July rainfall amounts observed in the average years of 1981 to 2010. On the other hand, the July 2017 rainfall amounts of southern Korea except Ahndong were 83.2 to 258 mm less than that of an average year.

It was expected that Changma in 2017 would start from Cheju Island (Fig. 2a). However, an inactive Changma front moved swiftly to central Korea, and then jumped to northeast China (Manchuria). For this reason, torrential rain occurred in Jirin city, Yeonbien of China, which received as much as 233 mm on July 19 (Fig. S2). The heavy rain band and area were observed

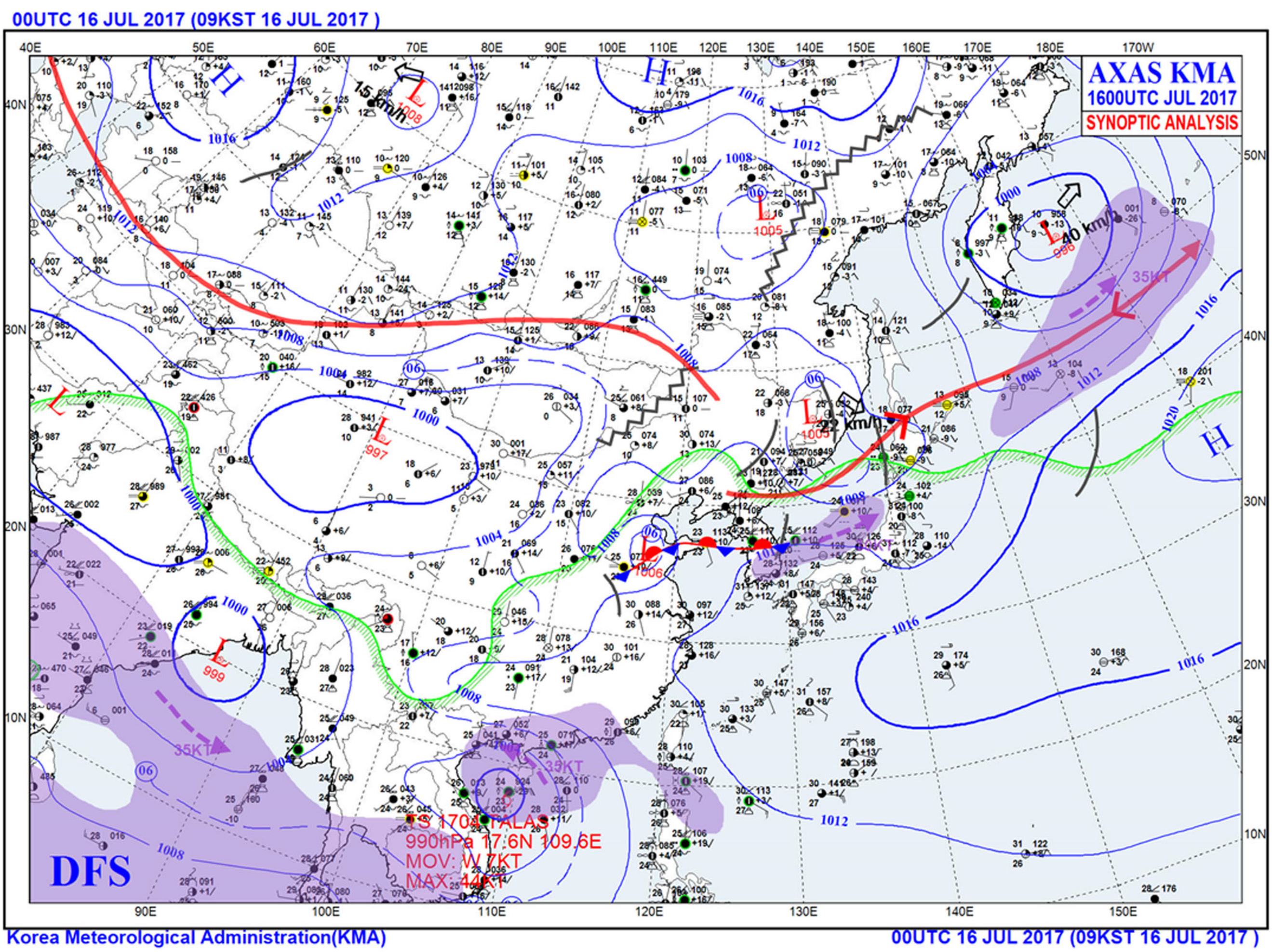

Fig. 3 A meteorological map (KMA) of July 16, 2017 showing a short quasi-stationary Changma front from the Shandong Peninsula in China to central Korea

in NE China between July 20 and 21 (Fig. S3a). Also, on August 3 and 4, torrential rain showers of 400 to 510 mm developed in Ansian city in Yonyeung Province of China.

In the past, the gradual movement of the linear Changma front characteristically produced steady rain for many days each year. However, in 2017, the front behaviour was quite irregular and it did not stay long in one area. As an example, the W-E oriented quasi-stationary Changma front was weak in its strength. In Fig. 2a, b, it is noted that the profiles of Changma rain are quite different from each other from the year 2017 to the year 2018.

Figure 3 shows a meteorological map of July 16, 2017. There was a linear quasi-stationary Changma front and it was just over 2000-km long from southern China to the southwest coastal region in Japan. With climate warming, air temperature in the north side of the stationary front was almost same as in the south side of it. This produced an inactive short Changma front. Historically, a long Changma front forms from southern China to southern Korea and southwest Japan from early June, and it gradually propagates northward to NE China. When the quasi-stationary front from NE China moves southward to Korea, a short rainy period develops in September which leads to a sudden drop in air temperature marking the beginning of autumn.

The Changma front in 2017 formed around Cheju Island in the early part of July when a weak front persisted for less than a week (Fig. 2a). On July 6, 2017 the Changma front moved northward quickly and joined another cold front that was moving southeast from Mongolia. The rainy front was persistently stationary in central Korea rather than in southern Korea. This weak Changma front in central Korea produced convective clouds and sporadic showery weather in the central region, as shown in the satellite image in Fig. 4. Importantly, the cloud band was not continuous. It was sporadically broken. Nonetheless, linear convective cloud streaks formed to produce heavy local showers, as shown in the radar images of July 16, 2017 in Fig. 5, rather than the steady rain which was common in and before the 1990s. On July 16, intensive cloud streaks developed in central Korea in about 10 h. The Changma front prior to the 1990s usually formed with the cool continental polar air, cP, and the warm-moist maritime tropical air, mT, in the NW Pacific. However, it was found that in recent years, the cP air has been warming as a result of climate change, and this has produced less contrast with the mT air for producing an inactive Changma front.

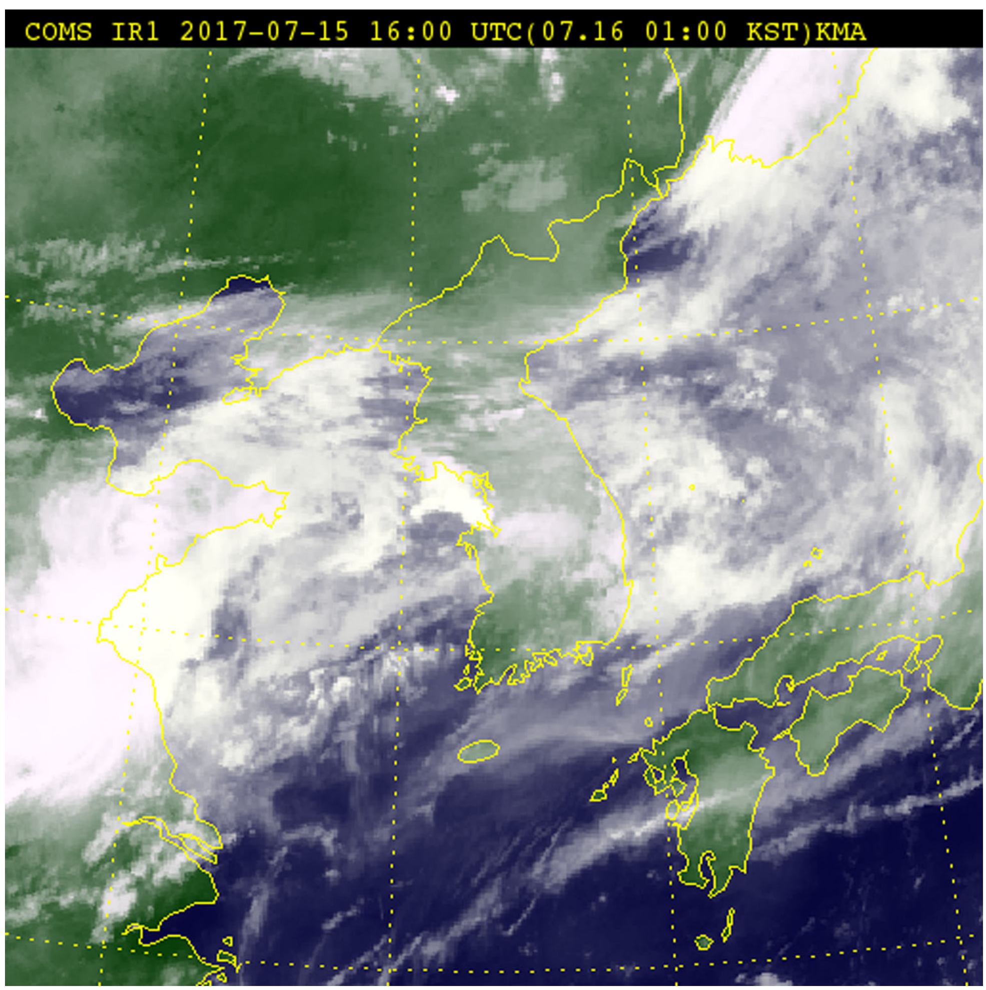

Fig. 4 A satellite image (KMA) of 01 KST, July 16, 2017 showing scattered convective clouds associated with the weak Changma front

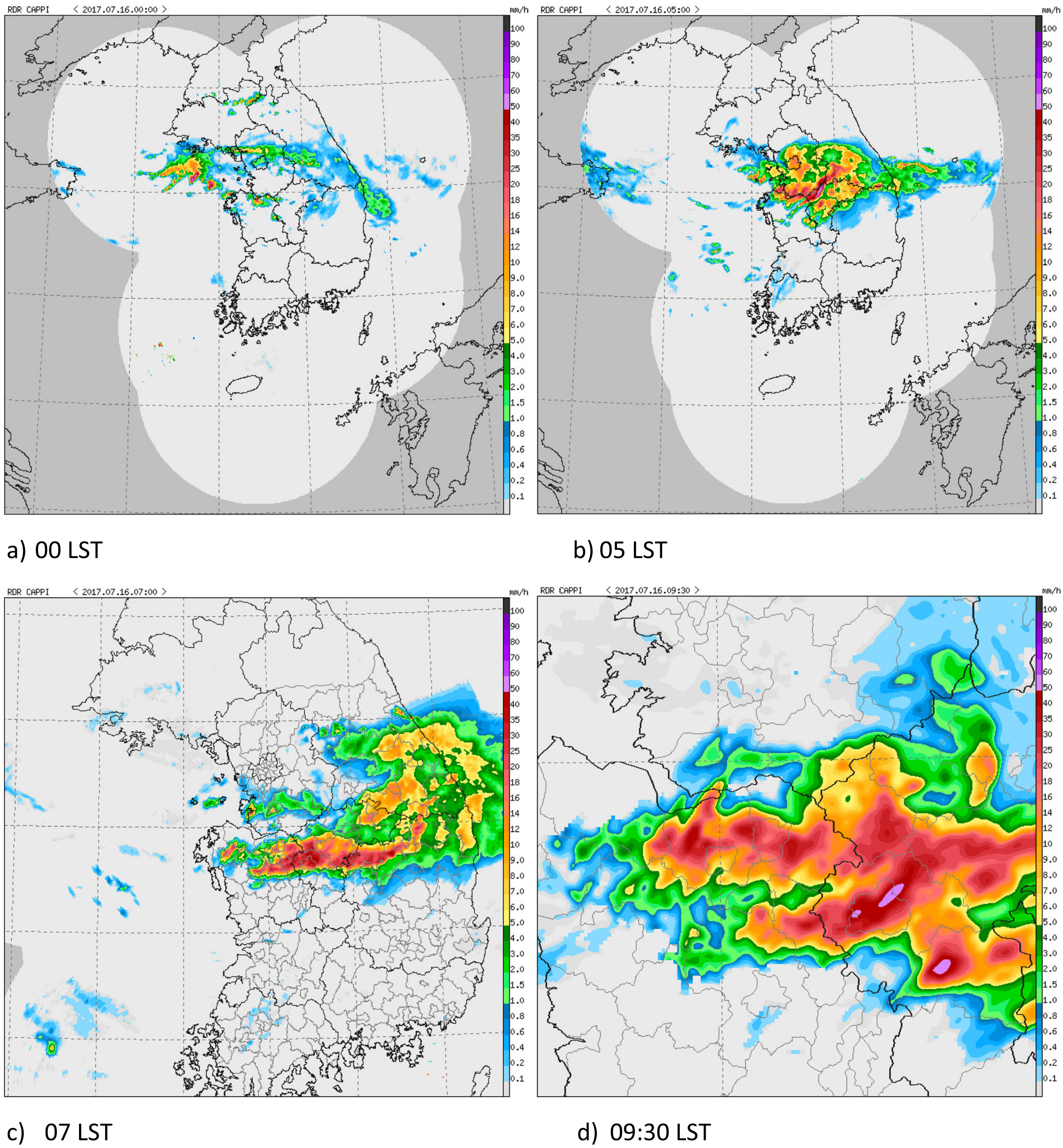

Fig. 5 Radar echoes (KMA) of **a** 00, **b** 05, **c** 07, and **d** 09:30 LST, July 16, 2017. Images show the development of convective cloud cells moving in from the Kyounggie Bay to Cheongju city and onward to the east

Convective rain clouds were formed (Kato 1989) in the radar echo near Incheon on July 16, 2017, and developed further inland in a few hours, as shown in Fig. 5. The linear cloud streak reached approximately 180-km long as it moved to the Cheongju area. In 4 h, torrential rain showers of 281.4 mm with numerous lightning strikes occurred. However, intense convective storms usually form at nighttime and last less than several hours. At a nearby measuring station, it was recorded that Cheonan received 232.7 mm, while the Korea Centre for Atmospheric Environment Research (KCAER) recorded that west Cheongju received only 116 mm in the same day. This indicated that the linear convective clouds had produced localized heavy rain showers. Notably, with the torrential downpour, Cheongju city recorded 7 deaths and damage totaling over a billion dollars.

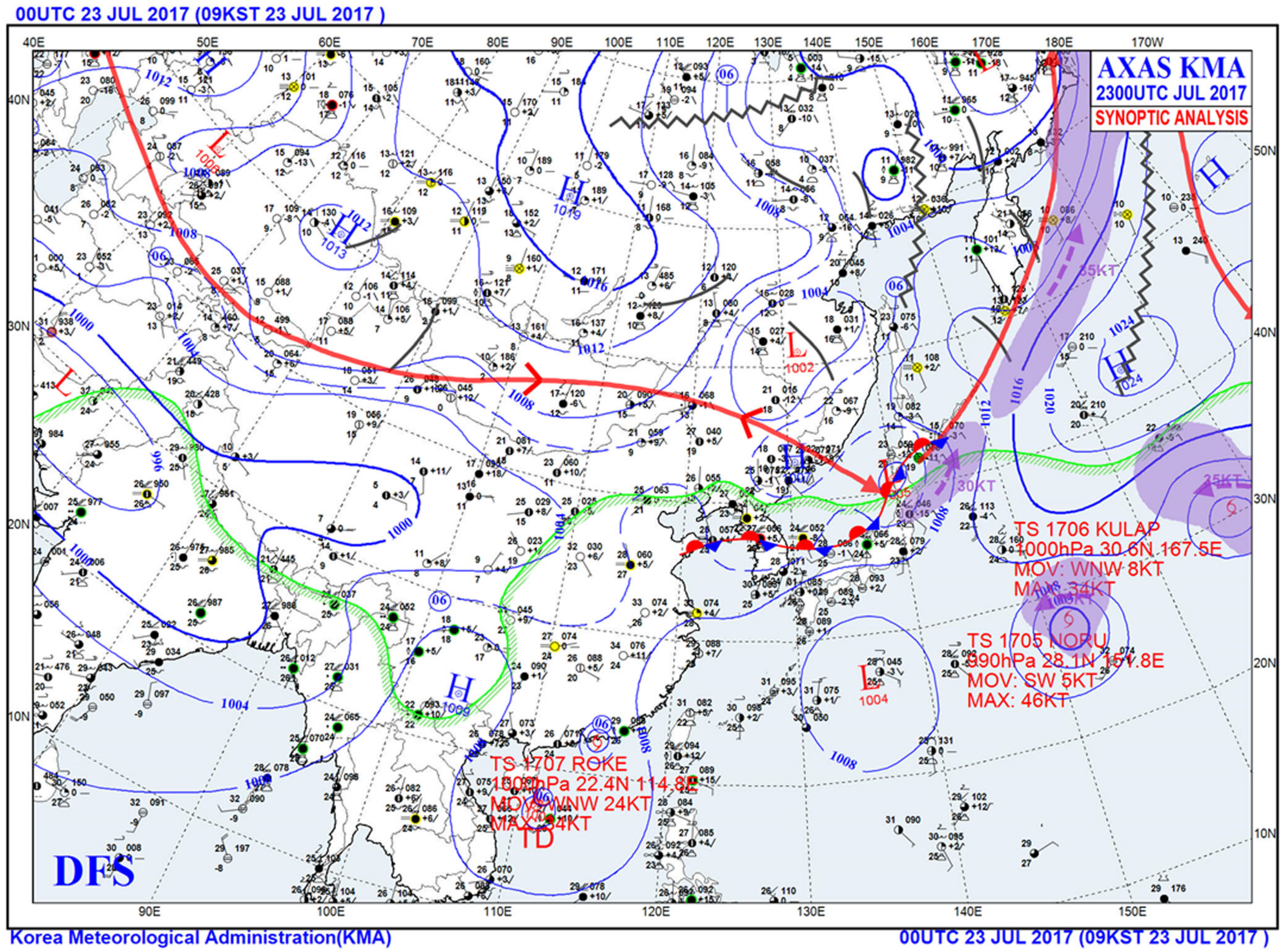

Fig. 6 A meteorological map (KMA) of July 23, 2017 showing a short Changma front over central Korea extending to western Japan

The meteorological map of July 23, 2017, in Fig. 6 shows that the Changma front situated over central Korea moved east to northern Japan. According to the radar echo in Fig. 7, a weak linear cloud streak was situated over northern Korea at 00 LST, and it developed significantly near the north sector of Seoul at 06 LST. The convective cloud then grew significantly at 8 and 9 LST. At 9 LST, torrential rain showers of 66.3 mm occurred in Incheon city and 125.5 mm in Seoul, and severe flooding occurred in that area.

Observations of Changma rainfall in 2018

Table 2 includes average monthly rainfall amounts of 30 years and monthly rainfall amounts observed in May, June, and July in 2018 as observed by the KMA. Rainfall amounts in May were 128% larger than that of the average years from 1981 to 2010. In June, monthly amounts were 151.6 mm which is almost the same as the average year. However, in July, monthly rainfall amounts were only 160.6 mm: roughly 57% of the amounts in the average years from 1981 to 2010. It is striking that in 2018, the much-needed Changma rainfall for the Korean biosphere was less than 43% of the average year.

In particular, for central Korea, the observed rainfall in July of 2018 was 19 to 53% lower when compared with the July rainfall of a normal year. The one exception was in Cheongju city which recorded a 15% increase (Table 2) due to localized heavy rainfall from a convective storm.

In general, Changma starts from Cheju Island which receives plenty of rainfall each July. Furthermore, each year, southern Korea records heavy rainfall amounts. However, in southern Korea, July rainfall amounts in 2018 were 19 to 73% lower than an average year. Most strikingly, Cheju Island had rainfall amounts in July that were 80 to 93% less than normal. The year 2018 was a notably dry year for Cheju Island. In 2017, southern Korea also had a lack of rainfall (Table 1) and droughts occurred in some localities such as the dried lake of the volcanic crater in Cheju Island (as shown in Fig. S3b). This indicates that the standard Changma characteristics have changed in recent years, and the important water resource distribution in Korea has changed with climate change.

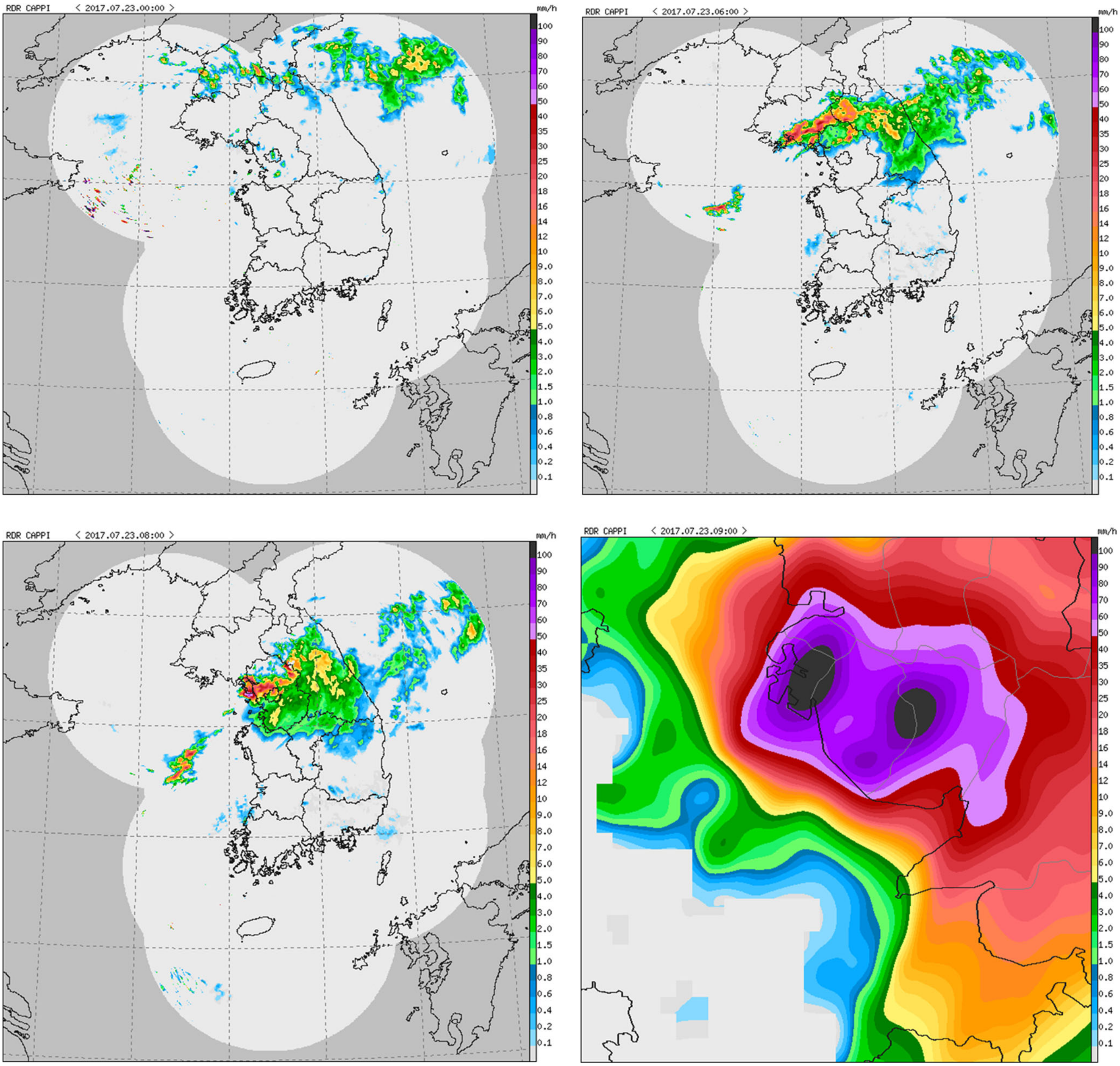

Fig. 7 Radar echoes (KMA) at **a** 00, **b** 06, **c** 08, and **d** 09 LST, July 23, 2017 showing the movement and explosive development of convective storms along the Changma front in central Korea

It should be noted in Table 2 that there were large differences in monthly rainfall amounts at each station. The differences were resulted from the localized rainfall phenomena in 2018, while Changma rainfall was relatively uniform among many stations prior to the 1980s.

In 2018, Changma rain started on June 19 at Seoguipo and Cheju city. On June 26, rainfall was recorded as 31.3 and 51.8 mm, respectively. The Changma front then moved up to central Korea and the observed rainfall ranged from 30.3 to 139.3 mm. In the following days, the rainy front moved southward and the rainfall measured in southern Korea was 1.0 to 131.1 mm on June 27 and 28, while there was 10.4 to 92.9 mm in Cheju Island on June 29 and 30. Figure 8; and Fig. S4 shows meteorological maps of June 26 produced in Korea and Japan, respectively. Again, air temperature contrast in the north and south sides of a Changma front was not significant with climate warming in the northern China (Qian and Zhu 2001). The radar and satellite images in

Fig. 9 indicate the Changma cloud band from China to Korea. The corresponding radar echo (from CMA) in Fig. S5 also shows that heavy rain extended to eastern China.

Table 2 Comparison of observed rainfall amounts (mm) of May–June–July in 2018 with the average data of same months in 1981~2010

Station	May	Normal	June	Normal	July	Normal	July differ	July ± %
Seoul	222.0	105.9	171.5	133.2	185.6	394.7	− 209.1	− 53
Inchon	158.9	100.3	144.0	112.0	148.8	319.6	− 170.8	− 53
Suwon	196.4	97.8	107.0	129.2	222.7	351.1	− 128.4	− 37
Chunchon	201.9	104.0	104.1	123.1	213.6	383.8	− 170.2	− 44
Kangreung	162.9	87.0	38.6	120.6	195.5	242.8	− 47.3	− 19
Uleungdo	131.6	105.1	65.0	115.3	184.9	170.2	14.7	9
Cheongju	92.0	88.3	63.3	144.1	324.9	282.7	42.2	15
Daejon	95.9	103.7	115.8	206.3	226.9	333.9	− 107.0	− 32
Seosan	147.7	105.2	162.3	138.4	152.9	273.4	− 120.5	− 44
Cheonju	122.1	91.5	137.2	167.9	169.1	299.6	− 130.5	− 44
Kwangju	85.4	96.6	222.4	181.5	84.5	308.9	− 224.4	− 73
Heuksan	91.6	102.4	177.9	174.7	217.9	226.0	− 8.1	− 4
Yeosu	134.5	146.5	291.8	213.7	149.7	291.5	− 141.8	− 49
Mokpo	89.3	89.2	162.0	173.1	67.6	236.7	− 169.1	− 71
Daegu	99.7	80.0	121.1	142.6	169.6	224.0	− 54.4	− 24
Ahndong	98.1	91.5	48.5	136.8	154.0	244.3	− 90.3	− 37
Pohang	71.6	85.2	89.1	141.6	164.1	203.2	− 39.1	− 19
Busan	155.8	157.4	276.7	206.7	122.1	316.9	− 194.8	− 61
Ulsan	95.4	108.1	127.6	176.8	160.3	232.3	− 72.0	− 31
Changwon	145.0	142.2	194.8	232.3	146.0	293.8	− 147.8	− 50
Cheju	98.8	96.4	211.1	181.4	48.7	239.9	− 191.2	− 80
Seoguipo	356.1	205.8	304.3	276.9	23.2	309.8	− 286.6	− 93
Mean	138.8	108.6	151.6	164.9	160.6	280.9	− 120.3	− 41
Difference	30.1		− 13.3		− 120.3			
%	128		92		57			

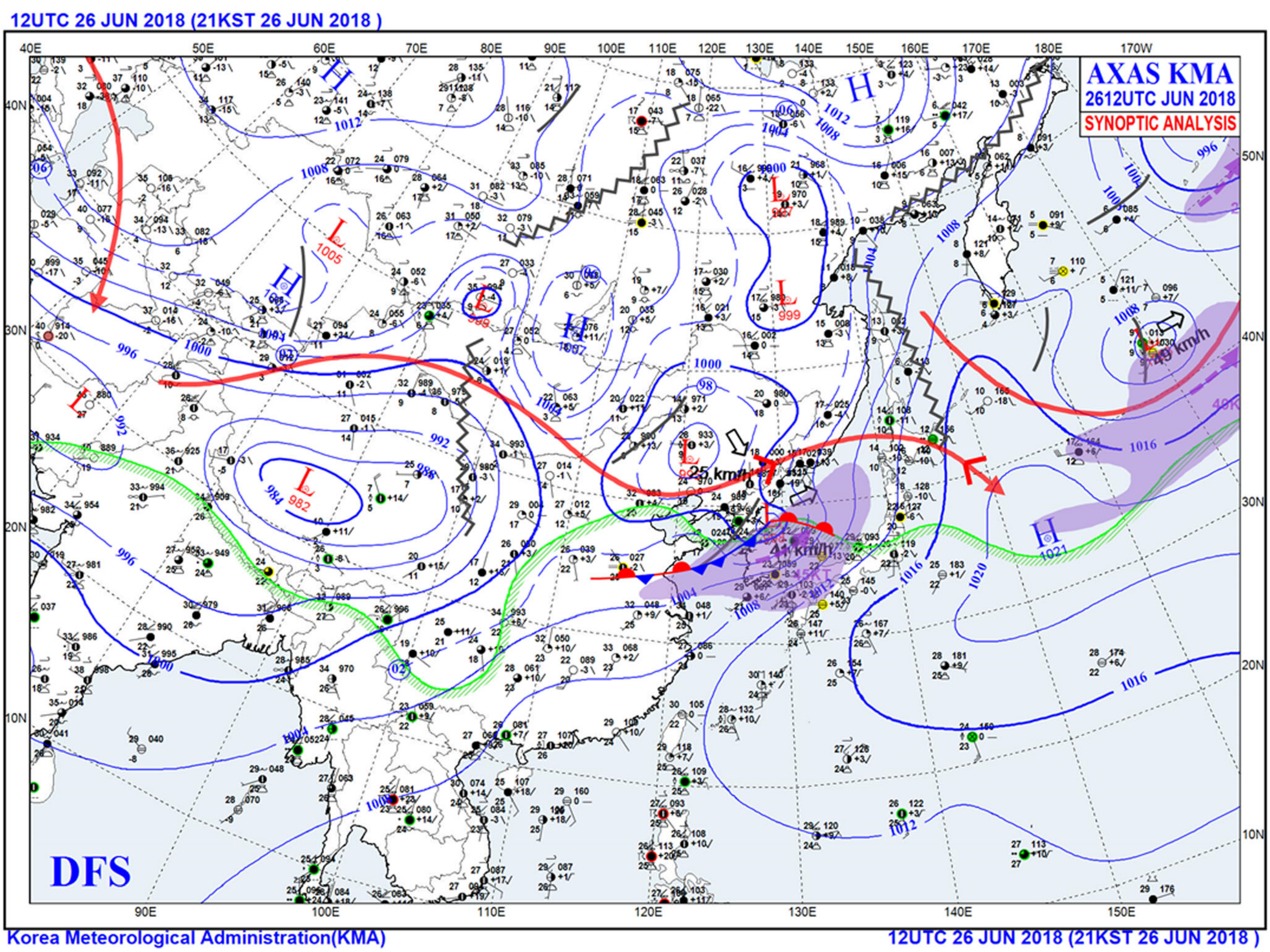

Fig. 8 A meteorological map (KMA) showing a short Changma front from eastern China crossing the Korean Peninsula on June 26, 2018

In 2018, on July 1 to 2, the majority of monitoring stations in Korea measured rainfall amounts from 47.0 to 196.2 mm with large differences at various sites. Seventeen stations had a record of over 100.0 mm in this 2-day period. At KCAER in west Cheongju city, 111.6 mm of rain with the Changma front was observed. The measured maximum hourly rate of rainfall was over 100 mm to produce the torrential rainfall. In addition, Fig. 10 shows that the length of the quasi-stationary polar front was relatively short. Air temperature contrast between north and south sides of the Changma front was not significant as one observed in before 1980s. This appears to be a result of climate warming in central and northern China and in Mongolia (Qian and Zhu 2001; Jugder and Chung 2002). Yet, the satellite image of Fig. 11 also shows that the broken rainy front extended from southern China via Korea to Hokkaido, Japan, and onward to the Pacific Ocean. Radar image in Fig. 12 shows that linear cloud streaks of heavy rain showers were situated over the Korean Peninsula and adjacent seas.

Figure S6a, b show meteorological maps of July 5 and 6, 2018 from Korea and Japan meteorological agencies, respectively. The Japanese map indicates an elongated Changma

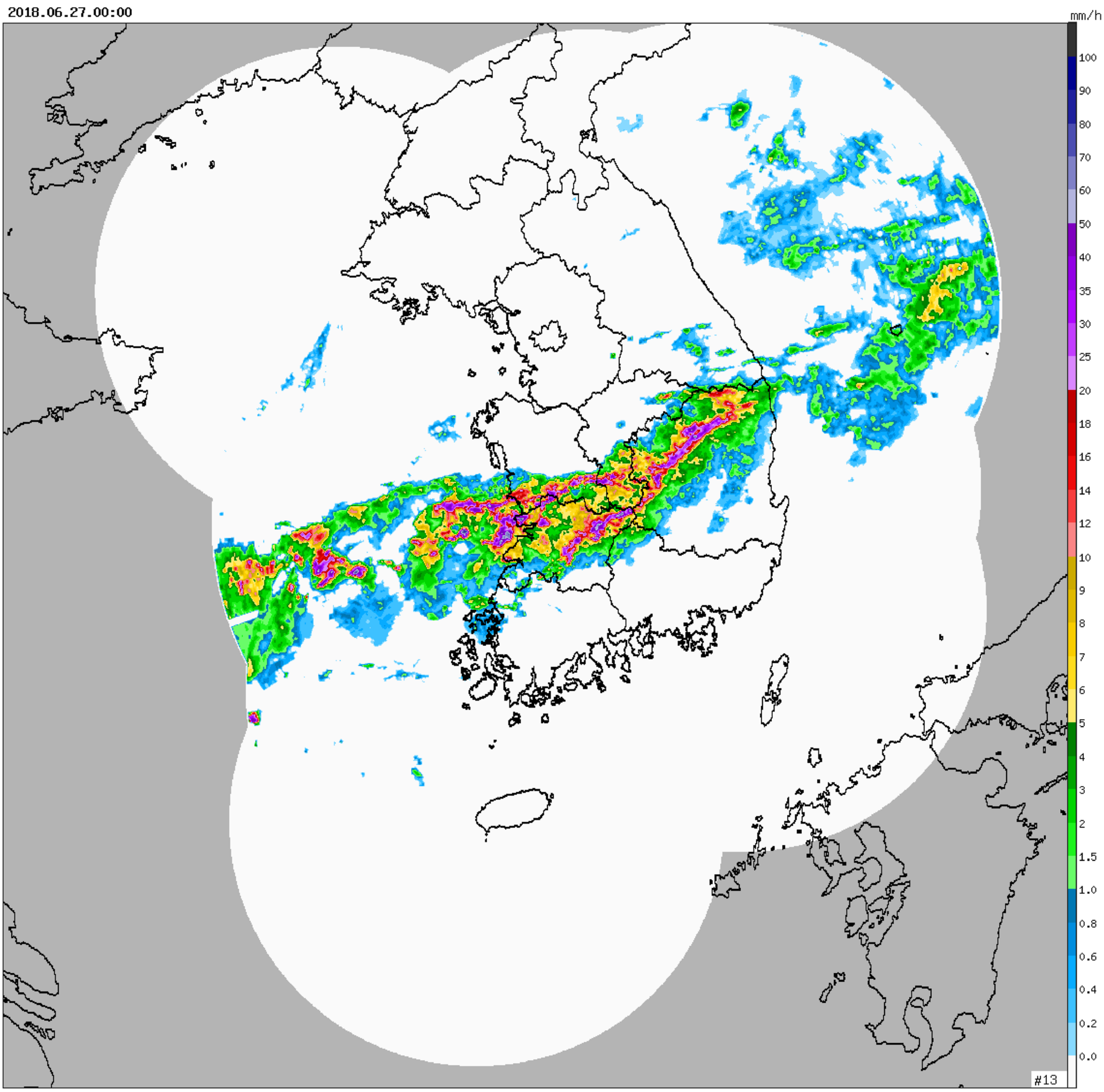

Fig. 9 Radar and satellite images (KMA) showing scattered convective cloud cells and linear cloud bands associated with a weak Changma front on June 26 and 27, 2018.

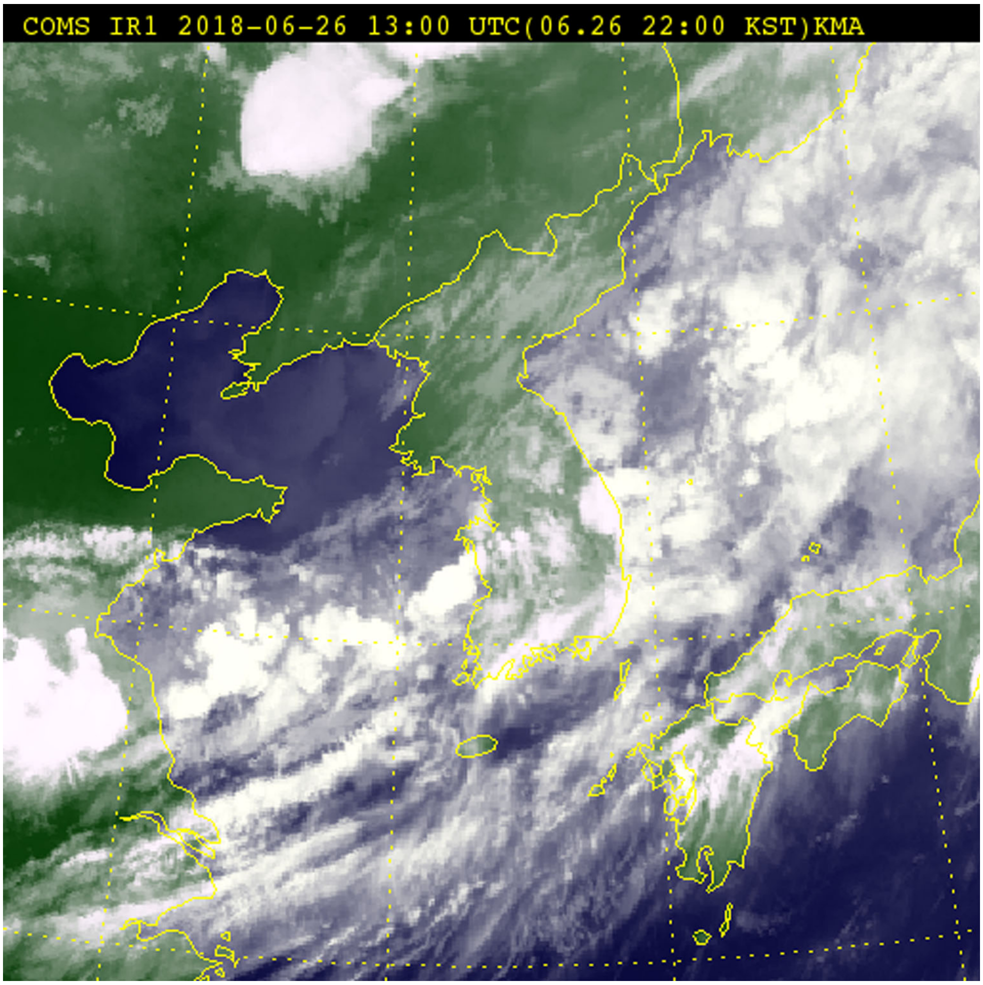

Fig. 9 (continued)

front from southern China to Japan and onward to the south of the Kamchatka Peninsula. In contrast, the Korean map shows that the Changma front was not continuous over the Korea South Sea where observed data is rare over the maritime area. The contrast in weather elements between north and south sides of Changma front was weak in the analysis of weather maps. A satellite image in Fig. S7 shows that the Changma front was situated over the Korea South Sea, and this did not continue to the Shanghai area in China. On July 6 and 7 measured rainfall amounts in southern Korea were in the range of 14.0 to 59.1 mm. A radar image and observed rainfall echo in southern China on July 6 in Fig. S8 indicate the situation of the Changma front in southern China.

Discussion

In July 2017, 16 days of 2 mm or more daily rainfall were recorded in Seoul. There were five showery periods with 159.5 mm on July 2 and 3, 232.0 mm from July 6 to 10, 75.0 mm from July 15 to 18, 133.5 mm on July 23, and 12.0 mm on both July 27 and 28. There were 9 rainfall days receiving over 10.0 mm per day including 92.0 mm on July 2, 67.5 mm on July 3, 34.0 mm on July 6, 16.5 mm on July 7, 32.5 mm on July 9, 144.5 mm on July 10, 42.5 mm on July 15, 22.5 mm on July 16, and 133.5 mm on July 23. There were only 7 days of heavy showery days above 30.0 mm per day and the total amount of rainfall was 546.5 mm. These represent 88% of July rainfall amounts.

Conversely, there were 11 days with no rain or 0.0 mm in July. If the days with rainfall less than 2.0 mm are included, there were 15 days. Climatologically, in the past, there were many more days of steady rain, and this confirms that Changma has changed.

With similar records, it was observed that in Cheongju in central Korea, there were 14 days of rainy days with less than 2.0 mm per day and no rainy days. As in Seoul, Changma rain started on July 1 and ended on July 28 in 2017. On Cheju Island, rainfall was recorded in Changma period as 11.7 mm on June 20, 39.8 mm on June 29, and 24.8 mm on July 11. These 3-day records indicate that Changma rain did not occur. In other areas, it began on July 1 and ended on July 17. The

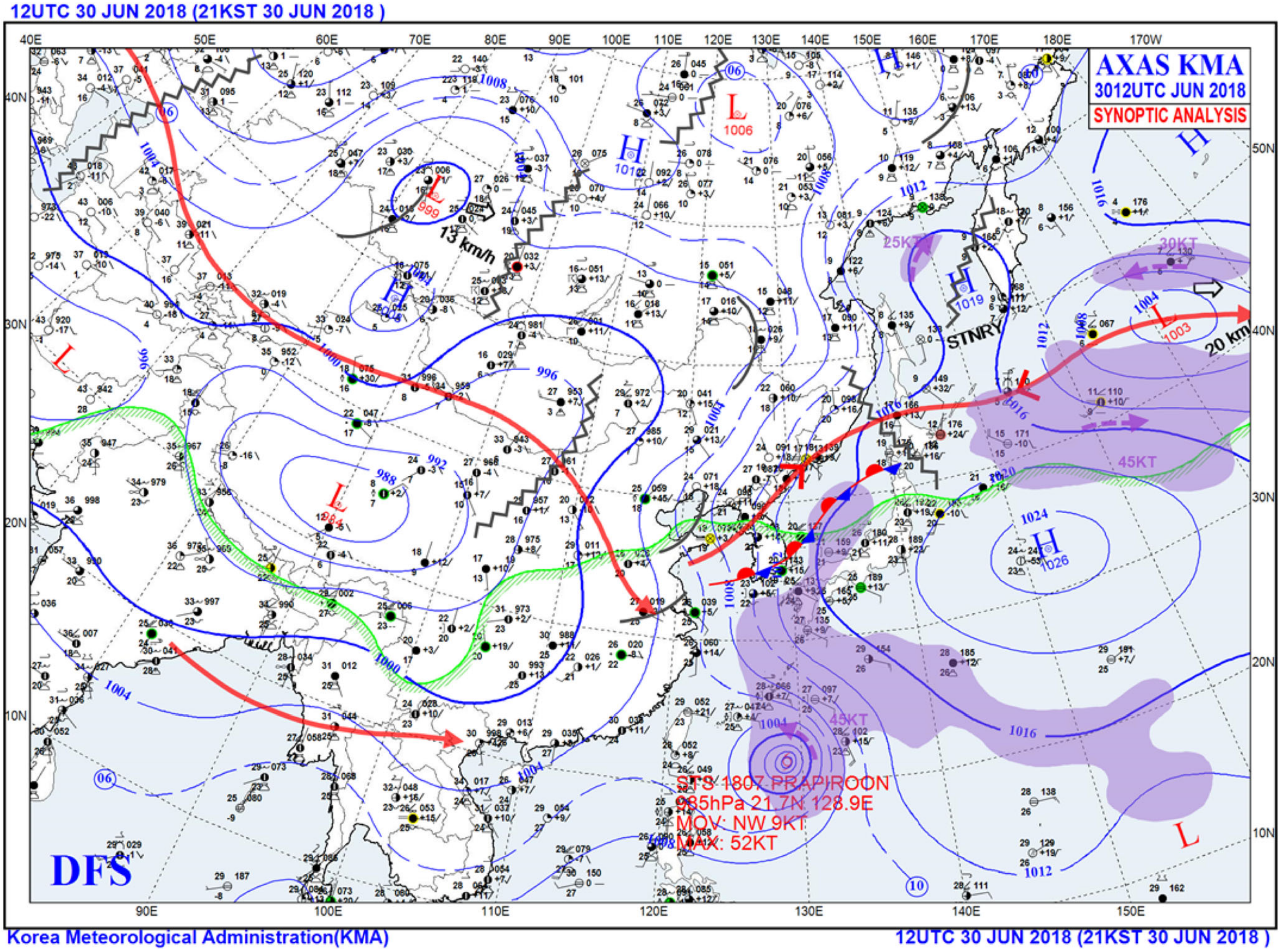

Fig. 10 A meteorological map (KMA) showing a short Changma front over the Korean Peninsula to Hokkaido, Japan, on June 30, 2018

onset and the last day of the Changma season varied and the length of the 2017 Changma was 2- to 3-weeks long.

Figure 13 shows the number of rainy days recording over 30 mm per day at five stations observed in 2017 and 2018. According to the data, in the 2017 Changma season, there were more heavy rainfall days in Seoul and Cheongju in central Korea, while there was a lack of rainfall in southern Korea. In 2018, however, there were more heavy rainfall days in June in southern Korea. In central Korea, heavy rainfall days occurred more in July 2018. These findings confirm a large variation in Changma characteristics. In recent years, regional rainfall amounts in a Changma season showed large variations each year (Chung et al. 2004), and these variations also occurred in 2017 and 2018 (Fig. 2a, b).

Meanwhile, the Changma season in 2018 started at Cheju Island on June 27 and ended on July 9. In Cheju Island, there were only 5 days with rainfall recorded at above 10.0 mm during10 days. This, in turn, suggests that the usual Changma season was not present in Cheju Island. In central Korea, it started on June 26 and ended between July 9 and 12, while it began in southern Korea from June 26 to 27 and lasted until July 5 to 9. There were many days with no rain during the Changma season, and strikingly, the Changma ended after only 2 weeks.

According to this study's examination with animation of geostationary satellite images of over 20 years, the Changma frontal zone from southern China via Korea to southern Japan was not as linear and continuous as it was before the 1990s. The linearity and continuity were broken in the Changma frontal zone, and they produced a discontinuity of rainfall days. Meanwhile, it resulted in many days of no rain during the Changma season. Moreover, this study observed that linear streaks of convective clouds developed to produce localized heavy showers. This, in turn, resulted in sporadic and intermittent local torrential-downpours rather than the steady and prolonged rainy days in Korea that occurred in the past.

The gradual northward propagation of a linear Changma front has changed so that now, it shifts abruptly to the north across a great distance until it joins with another cold front from Mongolia and NW China. It was also found that the strength of the Changma front was relatively weak with the warm continental air in the north side of the quasi-stationary

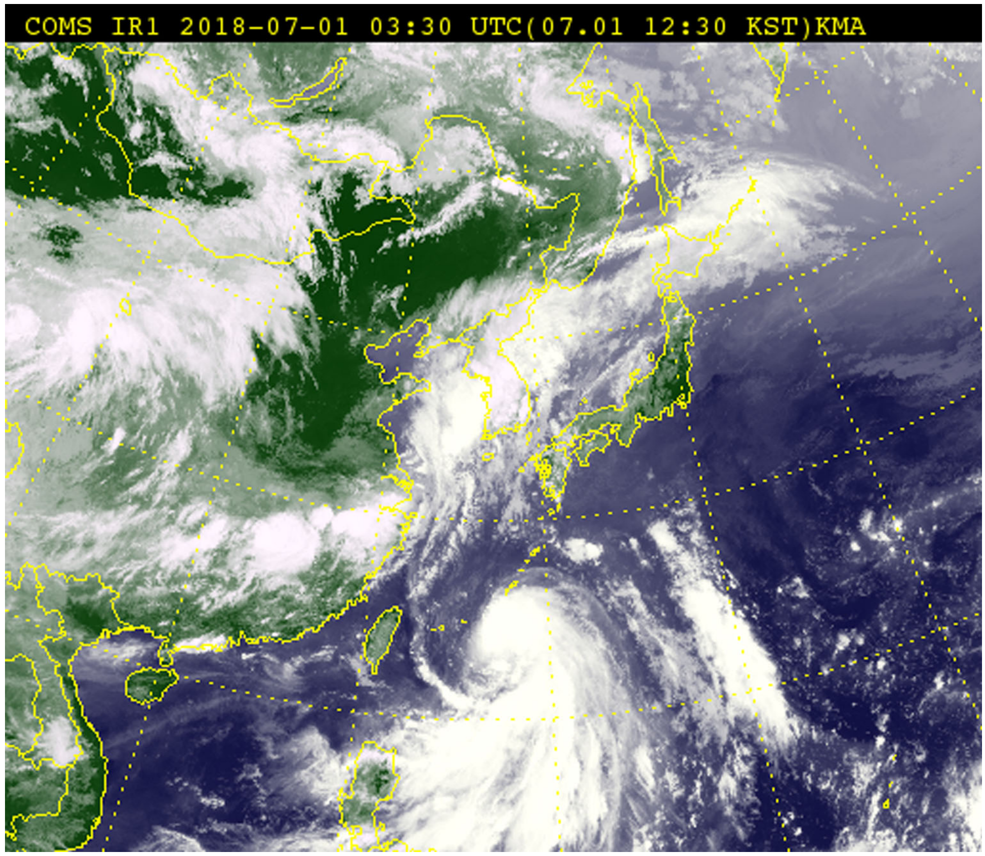

Fig. 11 A satellite image (KMA) of July 1, 2018 showing a (N-S oriented) Changma cloud band from southern China to Korean Peninsula and to Vladivostok, NE Russia. Another cloud band is over Mongolia and northern China and it will be joined with the Changma front

front. According to analysis of synoptic meteorology, this seems to be the consequence of current climate warming in Mongolia, China, and Korea (Chung and Yoon 2000; Qian and Zhu 2001; Shen and Varis 2001; Jugder and Chung 2002). Global warming and climate change are related to the increase of greenhouse gases and air pollutants (Chung et al. 2004; Kim et al. 2014). China and Japan are located on the upstream and downstream sides of Korea, respectively. In contrast to the 1990s, it has been found that, in general, the Changma front is not formed with a 3000- to 4000-km long extension and the active quasi-stationary frontal zone does not occur over East Asia, as before 1990s.

The formation of a Changma front is related with confluent upper and low-level air flows in the lee of the Tibetan Plateau (Chung 1977; Chung et al. 1976; Yasunari and Miwa 2006). The warm-moist air flowing around the southern barrier meets with the cooler and drier air streaming down from the north face of the Plateau. These can produce a discontinuity zone for making a Changma front in southern China in June (Sampe and Xie 2010; Xu et al. 2010). The newly formed quasi-stationary Changma front then gradually propagates north-eastward in late June and July to produce the Changma rainy season in Korea.

With climate warming over Mongolia and China, the strength of anticyclones and wind flows are observed to weaken (Chung and Dulam 2004). A schematic diagram is shown in Fig. 14 that an upper-air flow over the warmer continent produces weaker waves in the lee of large-scale mountains. This results in warm and weaker airflows (red stream line in Fig. 14) in the north side of a quasi-stationary Changma front. It is seen that a warmer and weaker upper-air flow deviates to the northward at a higher altitude and in the down-stream side, it moves southward to a lower altitude in the northern hemisphere (Chung 1977). Meanwhile, the contrast of weather elements in the north and south side becomes weaker in making a lesser active Changma front.

Convective clouds usually form in the afternoon hours, and they develop rapidly in the foothills of the mountainous area. The linear convective cloud band tends to move eastward and tends to propagate to the north and southward within the Changma frontal zone. The linear cloud streaks then develop rapidly to form torrential rain showers particularly during the night and early morning hours. The tops of convective clouds cool down quickly during the night, and rapid condensation to large raindrops occurs in the early morning hours. When the sun rises, it warms the clouds from about 10 AM, and the convective clouds tend to weaken and dissipate in accordance with cloud physics. The torrential rain that occurred on July 16 and 23, 2017 illustrates the formation of convective cloud

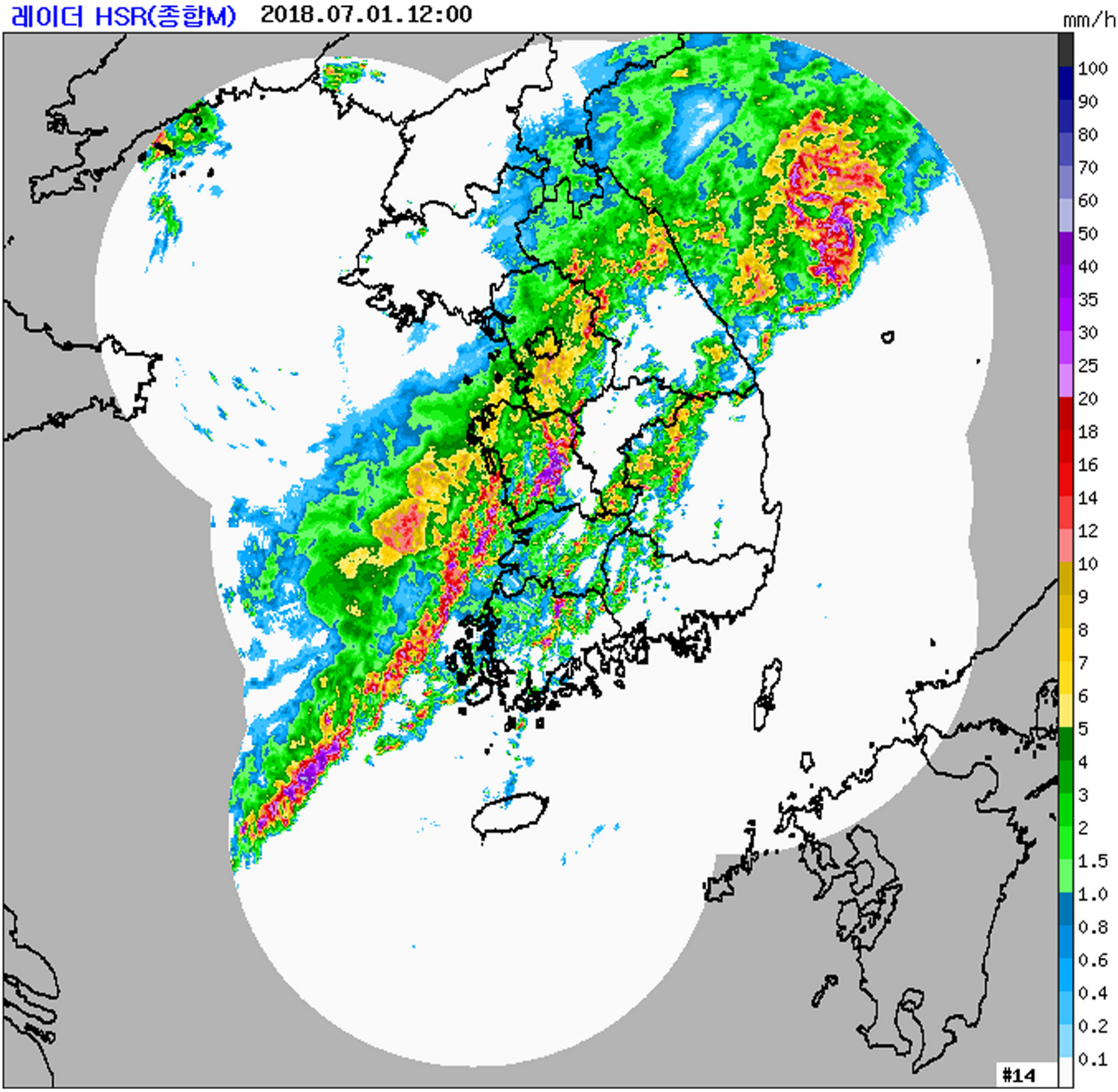

Fig. 12 A radar echo (KMA) showing (N-S oriented) linear cloud bands associated with Changma front with heavy rain showers over the Korean Peninsula and its adjacent seas on July 1, 2018

streaks (Luo and Chen 2015) and the weakening and dissipation of linear convective clouds.

As mentioned earlier, in general, Changma gradually propagated north and southward for about 30 to 40 days. This study found, however, that the front shifted to the north to join another cold front that came from Mongolia and northwest China. This produced a large amplitude of the Changma frontal wave and resulted in abrupt changes in weather and rain events on July 17, 2018, as shown in Figs. 15 and 16 with Fig. S9. Additionally, it was observed that the W-E oriented Changma frontal wave and resulted in abrupt changes in weather and rain events, as shown in Figs. 15 and 16 with Fig. S9. Additionally, it was observed that the W-E oriented weak Changma front was broken in its continuity of cloud zone, as shown in the satellite image of Fig. 16. The N-S amplitude of the Changma cloud band from central China (radar image of China in Fig. S10) to NE China was large, and it produced the irregularity of Changma rain at several stations. The synoptic pattern and satellite image showed the end of Changma rain over the Korean Peninsula.

The transformation of air masses was also studied carefully. Daily meteorological maps and satellite images were

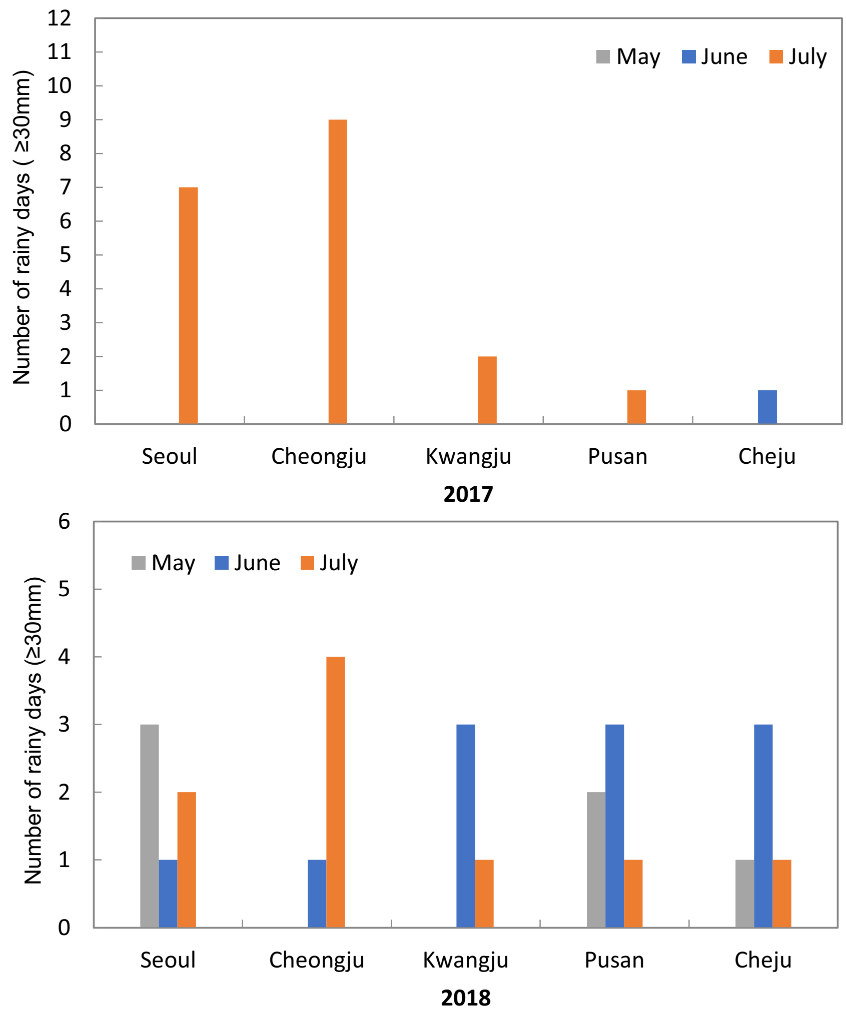

Fig. 13 Number of heavy rainy days (> 30 mm per day) at five stations in 2017 and 2018

scrutinized. According to the animation of satellite images over the past 22 years (Fig. S11a, b), it was found that a continental air mass, cP, is modified during its movement southeastward and to the sea. On the other hand, the Okhotsk Sea air mass, mP, impacts Hokkaido and northern Japan. Yet, it was observed that mP rarely moves southwestward to the Korean Peninsula. Conversely, the modified cP air mass over Mongolia moves to northeast China and the east sea off the Korean Peninsula. By

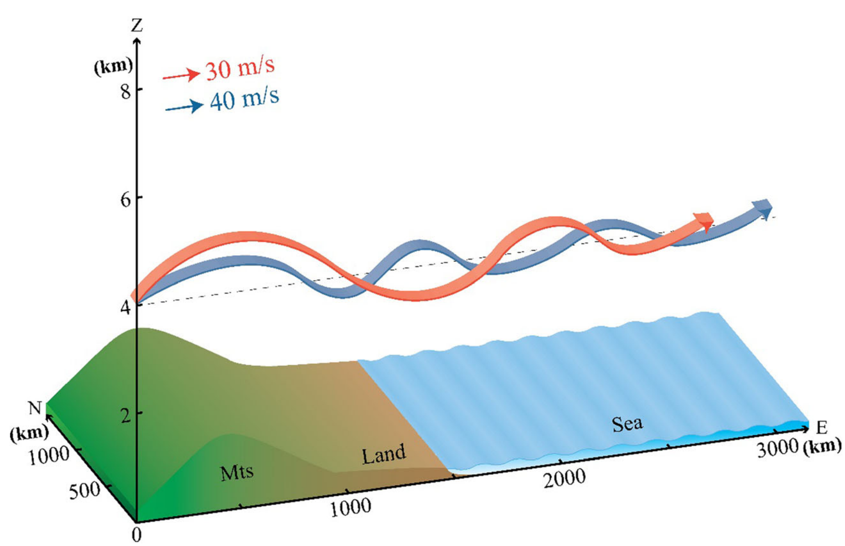

Fig. 14 A schematic diagram showing airflows over mountains, land, and sea. An airflow with lesser strength over the warm terrain produces a lee wave with the larger amplitude in downwind side

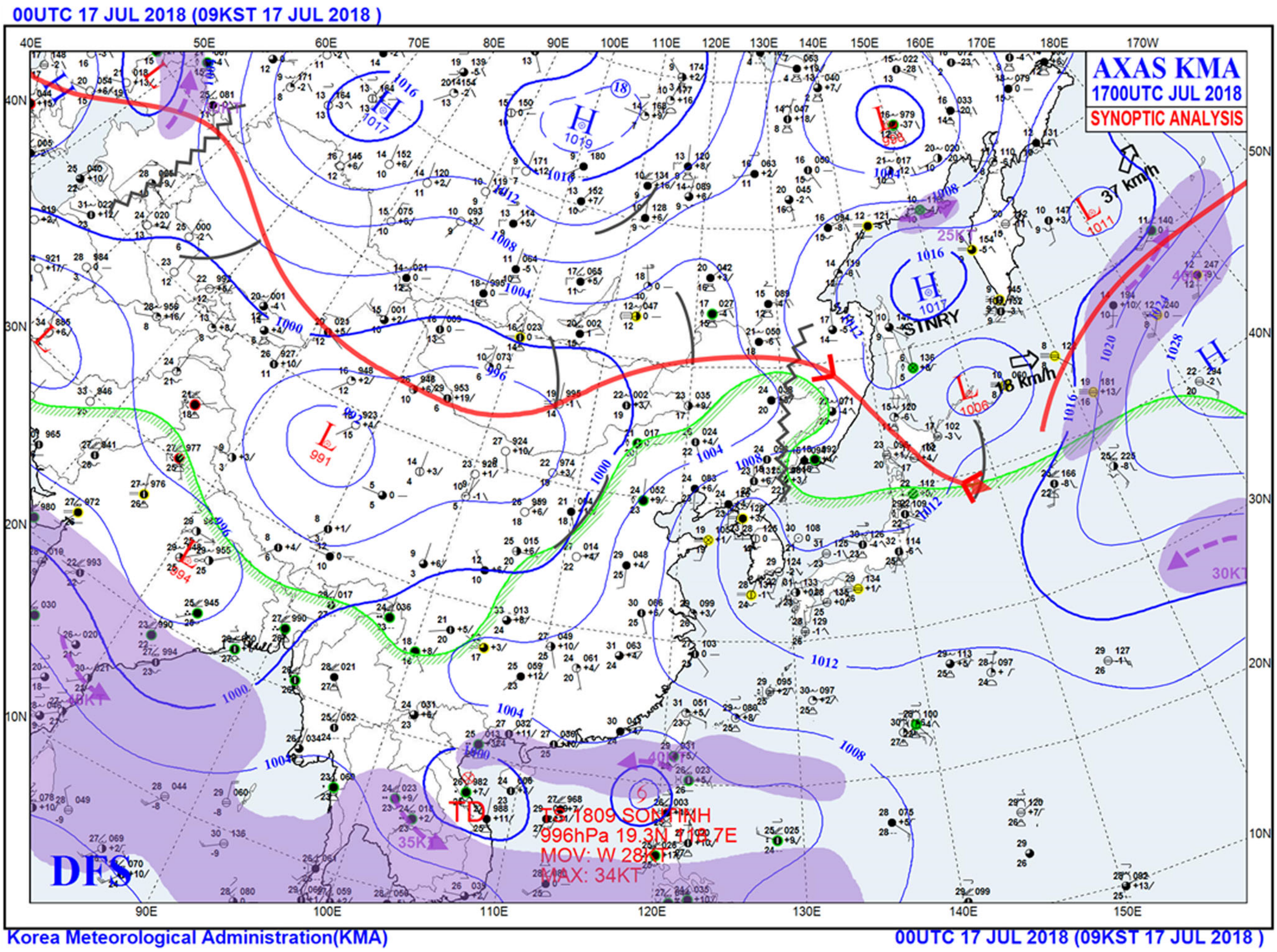

Fig. 15 A meteorological map (KMA) of July 17, 2018 showing the absent of a Changma front over China and Korea

the time the cP air reaches northern Korea, it has not combined with the cold mP air of the Okhotsk Sea of eastern Russia. When the cP air mass reaches northern Japan, however, it becomes mP with the Okhotsk air. As such, the mP air mass from the Okhotsk Sea influences the quasi-stationary front over northern Japan. In contrast, it was observed in this study that mP has no influence on the strength of the Changma front over Korea.

It should be noted that the prediction of daily Changma weather and rain in the past was relatively straightforward owing to the continuity and persistence of the Changma front. However, the irregularity and change of Changma front result in difficulty in weather prediction. Albeit, the present numerical weather prediction (NWP) scheme of short and medium ranges does carry out its predictive capabilities very well. Additionally, during recent Changma seasons, there were many days of no rain and partly cloudy conditions.

Figure S12a shows a 6-day forecast for June 25 to July 1, 2018. The figure indicates a band of linear clouds from China via the Yellow Sea to Korea and onward to northern Japan. Figure S12b also illustrates a 4-day forecast output on July 5, 2018. Although a subjective conventional forecast shows a large error in accuracy, the objective NWP outputs demonstrate well on the large cloud band containing rain showers from southern China to Korea and to northern Japan. Meanwhile, with the gradual N-S movement of a Changma front, general forecasting of Changma rain was relatively easier in the past, while the irregular northward movement of the front in recent years may be resulted in larger forecasting errors with the climate change.

After the ending of Changma days in 2018, very warm days persisted. From July 10 to July 13, daily maximum air temperatures above 30 °C occurred at the majority of stations in Korea until August 23. Record-breaking high temperatures of 38 to 40 °C occurred during August 1 to August 3. During the 43 high air temperature days without local rain showers, a severe drought was developed in many rural areas. Crops and orchards dried out in many parts of the region. Many farmers now also accept the reality of climate change, global warming, and changes in the Changma rain.

In addition, it is observed that the Changma rain usually produces cleaner air quality with wet deposition (Chung and Kim 2008). During the rainy days of summer, air quality

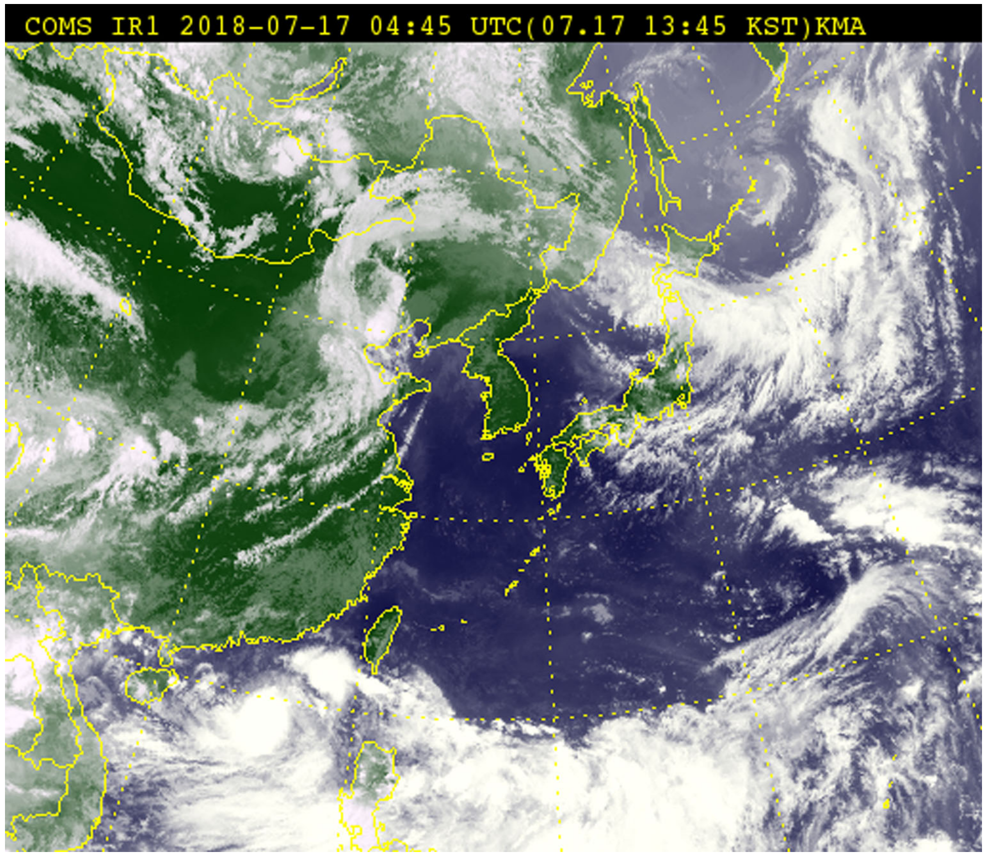

Fig. 16 A satellite image (KMA) of July 17, 2018 showing a weak Changma front with a large amplitude from central China to NE China

improves due to rain washouts and cleaner air coming in from the Pacific Ocean, and it will be included in another study.

Concluding remarks

The present study examined the changes in the East Asian summer rainy season called Changma in Korea, Meiyu in China, and Baiu in Japan. Changma is an important period that brings water resources to Korea. In 2017 and 2018, the Changma season occurred after a dry period and a drought in May and June. In general, it forms from late June and ends at the end of July. However, for 2017, it occurred at the beginning of July and ended in the middle and last part of July. In 2018, Changma was recorded at many stations to have started in the late part of June and to last until the early part of July (Fig. 2).

The length of the Changma season of the last 2 years was relatively short and there were many days of no rain or less than 2.0 mm of rainfall per day. In 2017, there were more rainfall amounts in July in central Korea as compared with the July rainfall amounts in southern Korea. A climatic irregularity was observed. Furthermore, a gradual northward shift of the Changma frontal zone was not occurring. Instead of steady rainy days during a Changma period, showery and intermittent rainy days were prevalent with the abrupt northward and southward shifting of a Changma front associated with linear convective cloud streaks.

On July 16, 2017 torrential rain showers occurred to produce 290.2 mm in Cheongju, central Korea. The sudden formation of linear convective cloud streaks in a few hours indicated pronounced features within the weak Changma frontal zone. Furthermore, in recent years, the frequency of heavy rain showers increased (Chung et al. 2004) and the length of the Changma season shortened from 4 to 5 weeks to 2 to 3 weeks, as observed in the earlier studies (Chung and Yoon 1999; Chung et al. 2004).

Until the 1980s, rainy days continued for several days and lasted after 4 to 5 weeks during a typical Changma season. In contrast, however, it was observed that intermittent showery rain commonly occurred for a few hours over a few days in July 2017 and 2018. There were many days of no rain in the Changma season. Climate change and warming in mainland China and Mongolia have warmed the cool air, cP, in the north side of the Changma front and it was of no help for the strength of a linear rainy front. Meanwhile, the significant contrast in weather elements between cP and mT air masses was found to be an important factor of the air environment for producing an active Changma front in the past. Furthermore, with less rainfall and shorter periods of rain-showery days in the Changma season, fungi in houses and buildings are no longer a prevalent phenomenon in Korea.

In conclusion, the changes of Changma are very important, and further studies are needed and we are investigating long-term data including climate change aspects. The Changma season has changed along with current climate changes and global warming trends. As a result, the characteristics of a conventional Changma season of steady rainy days are no longer prevalent. Torrential rain showers impact drainage systems and river management, both of which should be re-designed and re-constructed accordingly. In fact, even the word origin of Changma in Korea is not well understood. It is suggested that the current Changma climate system be renamed "summer rainy season," "rain shower season," or "summer rainy spell."

Acknowledgements We thank the KMA for providing science subvention of the Project (KMI2017-7020). Also, Ms. Cho JH has drawn a figure.

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