A Study on the Development of the Sustained Changma in 2007

Sang-Min Lee and Hi-Ryong Byun*

Department of Environmental Atmospheric Sciences, Pukyong National University, Busan 608-737, Korea

Abstract: In 2007, just after the recession of the Changma, anomalously long rainy period (from July 30 to August 15) occurred in Korea. To identify the cause of the sustained rainy period, we performed synoptic analysis and the associated air motions. The behavior of each air parcel trajectory associated with atmospheric motion was then investigated. As a result, three particular phenomena occurring at latitudes lower than 40°N were discovered. First, a mass of relatively cold air, referred to as E, made a deep intrusion from 20°N to 60°N. Second, this intrusion was accompanied by another mass of air called dE. It was colder and drier than E and originated from the mid-troposphere over the tropical ocean. Third, dE and E rotated clockwise three times over a period of 17 days over the Northwestern Pacific and blocked the westerly waves embedded in the zonal flow from propagating. Two additional phenomena were observed at latitudes higher than 40°N. First, the cold core system, while approaching from the west with low geopotential values at its center, was stagnated over Shanxi China. It enhanced the northward intrusion of dE and E, and then diminished. The subsequent low system showed similar evolution as the first one. Second, a warm core anticyclone was formed over Lake Baikal, blocking the westerlies for 13 days and contributed to the persistent northward incursion of warm moist air. Moreover, a horizontally extended intrusion of upper level clouds from the tropics to 50°N, which may be interpreted as a tropical plume, was found around the end of the period (from August 12 to 15, 2007) with successive tropical nights over Korea.

Keywords: dry equatorial air lump (dE), equatorial air mass (E), tropical air mass (T), long rainfall, Changma

Introduction

In 2007, there were limited quantities of rain during the Changma period, but continuous rainfall was recorded following the Changma period over the Korean peninsula. In the course of investigating the causes for this unprecedented phenomenon, we found a very rare phenomenon where relatively cold and dry air at 500 hPa over the Northwestern Pacific moved from the southern low-latitudes of the ocean to penetrate north into the high temperature air current over the Asian continent. There has never been any record of cold and dry air at 500 hPa over the Northern Hemisphere moving from the southern low-latitudes of the ocean to penetrate north into the high temperature air current over Asia, thus offering the main topic for this study. Although previous studies have stated that equatorial air masses (E) are found more commonly in low latitudes than tropical air masses (T), such instances have seldom been applied in the analysis of atmospheric circulations. In addition, many studies did not understand the very existence of E nor have presented a different theory. Therefore, we began with the fundamental theories of air masses.

It is safe to assume that the notion of E was first used by Stahler (1951) and Grimes (1951). They emphasized the important relationship between many recorded natural disasters in the mid-latitudes and E. This assertion was extended further by Barry et al. (1968), Butzer (1968), and Oliver and Fairbridge (1987) and has now been established as a self-explicit theory. These works defined an E as an air mass generated in between the northern latitude of 15° and the southern latitude of 15°. Although they are similar to T in being very hot, humid, and unstable, they are relatively colder and incomparably more humid than T at the upper levels. The notion of E and not mE (maritime Equatorial air mass) is used because of the absence of any continental E. However, Djuric (1994) provided a different opinion. He simply defined E as air displaced from the austral winter into the boreal summer over the equator. It was added further that when this air reaches the northern hemisphere, it becomes a westerly through the effects of preserved...
momentum; such air is relatively colder than the neighboring winds because it is moving from the winter hemisphere. In addition, he said that it normally moves northward from the lower levels to the mid-latitudes. However, Djuric (1994) also noticed that such occurrences are very difficult to find.

Ahrens (1996) defined E as an air mass that is relatively warmer and more humid than T. In addition, Baum et al. (1997) classified E to have a surface temperature greater than 32°C and T with a temperature below 32°C (Table 1a). In East Asia, only the work of Ahrens (1996) has been widely introduced (Jung, 2004), and there is no evidence of any interests in the work and findings of Djuric (1994). However, there are three critical problems with the statement that “equatorial air masses are warmer than tropical air masses”. First, it is true that colder air is found in the southern part of T, in other words, toward the equator. However, no warmer air is found there, and there is no logical reason to believe in the presence of any warmer air in the region. Second, if in fact E is warmer, there is no reason to distinguish it from T. Third, none of previous studies has ever premised and concluded that E is warmer than T.

The confusion over the exact definition of E has continued down to the present. In the program (V1.2) of Lopez-Cotin (2005), which relied on the theories of Ahrens (1996) to distinguish different types of air masses, the use of the surface temperature has been discarded as the method of distinguishing E. Furthermore, there was a strong need to revise the standard of classifying different air masses by using precipitable water, and this was reflected in V1.3 of the program by Lopez-Cotin (2007) (Table 1b). These confusions signify that the definition of the term E has not been finalized. Regarding this, the AMS glossary (Glickman, 2000), incorporating the views of Grimes (1951), recognized the existence of E but added that the theoretical works of some meteorologists make it clear that the definition is still incomplete.

Saito (1965) tried to determine the boundaries of different air masses using specific variables (Table 1c). Applying specific humidity and pseudo-equivalent potential temperatures at 850 and 700 hPa, air masses were classified into five different categories, polar, tropical, modified tropical, monsoon, and modified monsoon. Here, there was no reference to E, and the study was not complete enough to explain exactly what the word, “modified” meant in the terms, “modified tropical and modified monsoon”. As can be seen, no single study has ever been successful to define the boundaries of the different classifications of air masses. However, we acknowledge the fact that different regions have different air masses and that the majority of weather forecasts are being produced based on the characteristics of these air masses. Therefore, the necessity of further studies in this field cannot be overemphasized.

Investigations of the movement of E from the low to the mid and high latitudes are not found in Asia, but there exists rare report in other regions around the world. Heidorn (2005) claimed that it was rare for E to reach the United States and that they never reach Canada. However, Heidorn (2005) failed to provide specific examples or evidences to support his claim. On the other hand, in EBO (2007), E was distinguished from T based on the fact that E in the mid-latitudes over Africa brings heavy rain. Although these two studies recognized the importance of E as an important meteorological element, no further study has been made or reported to develop such findings. In addition, no research works exist that examine the northward intrusion of equatorial air currents, penetrating through the high temperature zone of T into higher latitudes.

It is very difficult to find any studies concerning the effects of T on the weather in the mid-latitudes. Although Seluchi and Marengo (2000) showed a profound interest in air masses, they excluded any investigation on their classification and movement. The Reserved Oriented Monsoon Trough (ROMT) is a good example of a meteorological phenomenon where lower level air moves from the tropics to north and into the mid-latitudes. A monsoon trough is a low pressure trough tilted from southeast to northwest
through easterlies, the ROMT is a deep intrusion of air mass in association with the easterlies and southwesterlies from the equator into the mid-latitudes over the northern hemisphere. However, no study specifically has provided an explanation by relating the ROMT to E.

Tropical plume refers to the direct movement of upper level clouds from the tropics to the mid-latitudes (Iskenderian, 1995; Knippertz 2007), where moisture often accumulates in the lower levels. Such plume can function as the foundation for various extraordinary weather phenomena, including hazardous weather. Iskenderian (1995) showed that there were a total of 1,062 reported cases of tropical plume over a period of ten years (1974-1984, except 1978), during the winter season. With various names, such as “tropical intrusions”, “cloud surges”, “cirrus surges”, “moisture bursts”, and “tropical plumes”, this phenomenon was commonly found during the winter season (Knippertz, 2007). There has not been a previous study in Asia on the summer occurrences of tropical plumes nor on the movement of air masses in relation to them. In addition, ENSO has yet to produce any study showing the effects of T or relating these findings to different air masses.

The main purpose of this study was to demonstrate the northward intrusion of relatively cold air currents in low latitudes after the end of the summer Changma on the Korean peninsula in 2007. The results of this study allowed us to evaluate many new findings, which have made further work necessary in the fields of summer forecasting and climate studies.

Data and Analysis

This study incorporated GDAPS (Global Data Assimilation and Prediction System) geopotential height, temperature, and wind vector data (1.25°×1.25°) from the Korea Meteorological Administration, and NCEP/NCAR analysis data (2.5°×2.5°) that included geopotential height, temperature, wind vector, precipitable water, tropopause height, streamline, and omega information. Precipitation data from 61 stations, along with weather charts and satellite images from the Korea Meteorological Administration, were utilized in the study. Rather than using pseudo-equivalent potential temperatures, wet-equivalent potential temperatures were calculated to determine the equivalent potential temperatures. The trajectory analysis was conducted by using the HYSPLIT 4 model (Hybrid Single-Particle Lagrangian Integrated Trajectory Model, Draxler and Hess 1998; Draxler and Rolph, 2008).

Redefining Air Mass

Although the redefinition of the term “air mass” will be expressed through the results of this study, for convenience of explanation, we will first introduce this redefined term. Among the many diverse theories on E, we followed the definition of Djuric (1994), which defined E to be more humid and cooler than T. First, the upper level air over the Asian continent is a continental T due to its warm temperature (Fig. 1). Next, the maritime air mass over Southeast Asia, being cooler than its neighboring air masses but having a relatively high dew point temperature and equivalent potential temperature, was classified as E. Therefore, we classified areas having temperatures below −5°C as E and above −5°C as T at 500 hPa. Because T exhibits a high temperature, and E has high humidity, the equivalent potential temperatures for both air mass classifications were set at above 330.5 K (Tables 1, 2).

E has been defined as having a level of precipitable water greater than 6.0 cm (Baum et al. 1997; Lopez-Cotin 2005, 2007). The precipitable water for T was once revised from 3.0-6.0 cm (Baum et al., 1997) to 2.5-6.0 cm (Lopez-Cotin, 2005). However, these values were calculated from observations over the Atlantic Ocean. During the period of the analysis, there were virtually no reported cases where regions with more than 6.0 cm of precipitable water were not accompanied by a tropical cyclone in the northwestern regions of the Pacific. The high level of precipitable water in regions neighboring tropical cyclones is
mainly due to the increased convergence resulting from the low pressure, thus making it unnecessary to classify it as an air mass. Therefore for this study, an amount of precipitable water above 4.0 cm was classified as T while an amount of precipitable water above 5.0 cm was defined as E (Table 2). This coincides with the theory of Liu (1986), who stated that the precipitable water over tropical oceans exceeds 4.0 cm.

In Fig. 1d, areas with less than 4.0 cm of precipitable water within 100-140°E, and close to 30°N, are found in the East China Sea, in the ocean to the south of the Korean peninsula. These regions exhibited less precipitable water than T. We had to distinguish them from other areas because, even though they were situated over the ocean, they were drier than E. Therefore, we defined these regions as “dry equatorial air lumps (dE)” and focused on them in our analysis.

In addition, tropopause height was also applied in the air mass analysis. Although in Baum et al. (1997), an air mass below 135 hPa was classified as E, while an air mass at 135-225 hPa was T, this definition does not apply in Asia. Nearly all of the areas in the mid- and low-latitudes, as well as some high-latitude areas, show a value of less than 135 hPa (Fig. 1i). Also,
these distributions showed no variation between July 18 and August 15. The same problem was found for surface temperature. Areas classified as E with temperatures over 32°C were often found in northern continental areas, where the temperatures above the ocean were all below 28°C. There were no indications of significant changes or characteristics in this surface temperature distribution during the analysis period (Fig. 1j). Therefore, this study excluded all of the works distinguishing E and T based on tropopause height and surface temperature.
Northward Intrusion of Relatively Cold Air Lump and Increased Precipitation after the End of the Changma

July 28, relatively cold dry air lump at an upper level over the ocean

There were two reported zones at 500 hPa with high temperature on July 28 (Fig. 1). The first was situated over the Northwestern Pacific and the other was over China (40°N, 100°E). There was a strip of low temperature zones stretching from south to north between these two high-temperature regions (shaded area in Fig. 1a). We can see from Fig. 1a, b, and c that zones with relatively lower temperatures, higher dew points, and equivalent potential temperatures than their neighboring zones were concentrated over the Philippines in Southeast Asia, south of 20°N. Although the dry regions of Fig. 1d were related to the low-temperature regions of Fig. 1b and c, there were humid zones surrounding the dry zones to the north, thus showing a streamline structure similar to a blocking phenomenon.

In the 850 hPa fields (Fig. 1e, f, g, and h), there was a northward path for relatively cold dry air lump and its location was similar to those at 500 hPa. Concerning the distribution of equivalent potential temperatures, the only similarity is that high values were detected over China (Fig. 1c and h). Although the center of the North Pacific anticyclone was located at the eastern coastline of China, it was comparatively warmer than its neighboring zones, unlike the results at 500 hPa (Fig. 1f).

Northward intrusion of relatively cold air lump

Figure 2a represents the 500 hPa temperature fields obtained from an analysis of the GDAPS data from the Korea Meteorological Administration for 5 days, between July 25 and 29. On July 25, the high temperature zones (gray zones) exceeding −5°C,
located south of 40°N, were reported to be the hottest regions, making them T. E, with temperatures lower than −5°C, was located over the lower latitudes (Fig. 2). On July 25, the E was limited to the lower-left zones (south to 20°N, 120°E), but connected itself to the northern high-latitudes on July 26. In other words, the relatively cold air lump in the lower latitudes intruded north into the higher latitudes. In addition, in locations below 20°N, the total area with low temperature zones of less than −5°C increased dramatically.

The northward intrusion of low-latitude relatively cold air lump was different in the temperature fields represented by the NCEP/NCAP reanalysis data. Because of its low resolution (2.5° interval), the NCEP/NCAP reanalysis data was not as explicit as the northern penetration shown in the actual weather chart (Fig. 3) and the GDAPS data. This is why the northward intrusion of relatively cold air lump into higher latitudes had not previously been found in other studies. The satellite pictures in Fig. 3 show that the northern movement of the relatively cold air lump created large-scale cloud bands to the east of the low pressure. (Cloud band is located over land in Fig. 3 but cold air lump over seashore at 29 July, 2007 in Fig 2a.) In other words, the northern movement of relatively cold air lump was not created because of the cloud bands but rather it caused many of the clouds to the west. In an analysis of trajectories (Fig. 4a), the air mass that existed at 953 hPa (300 m)
above Hainan China (20°N, 110°E) on July 24 ascended north to the central region of China on the 28th, and then moved to regions in Mongolia on the 30th. The four days of accumulated trajectory analyses for three altitudes (500, 1,000, 1,500 m) also showed a rapid movement into the higher latitudes (Fig. 4b). There were almost no records of eastward movements. As can be seen from these records, there have been no previous studies on the northern intrusion of relatively cold air lump from low-latitudes. In addition, it is unclear whether a similar situation has ever existed in the past.

Increased precipitation after the recession of the Changma

Figure 5 represents a time series for the average daily rainfall recorded from 61 different observation stations in Korea. On July 29, the Korean Meteorological Administration announced the end of the Changma, but with the exception of three days (July 30, 31, and August 2), there was continuous rainfall for the next 17 days, until August 15. From August 4 to 14, except for one day (August 11), the recorded rainfall was greater than the average, giving this period the most recorded rainfall for the year 2007. Evidence for continuous rainfall after the Changma period has also been found for other years, including five of the past ten years, namely 1998, 1999, 2002, 2005, and 2007. There have been no explicit studies or evidence to show whether this phenomenon is related to climatic changes.

Northward Intrusion of Relatively Cold Air Lump and a Block to Eastward Movement

The development and dissipation of the cold core anticyclone

As the Changma period comes to an end, a phenomenon where the North Pacific anticyclone is divided into two parts has been found (Fig. 6). Tropical high pressure, frequently referred to as the North Pacific anticyclone, is frequently established in the closed curved areas of 5,880 gpm at 500 hPa, and is divided into relatively cold and warm zones. On July 29, an anticyclone with an isobar of 5,880 gpm over the East China Sea was accompanied by temperatures below −5°C, with an eastern one above −5°C. Commonly, migratory anticyclones move in pairs...
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During the autumn, winter, and spring seasons in the westerly belts of the mid-latitudes and are classified into a cold anticyclone to the east and a warm anticyclone to the west (Djuric, 1994). However, in this case, the western one was colder, showing a completely opposite result. At 700 and 850 hPa, the classification of the anticyclones became clearer, but at 500 hPa, the anticyclone to the west exhibited colder temperatures on July 29.

At all three altitudes, a southerly was induced at the northwestern side of the cold core anticyclone. Therefore, relatively cold air lump from the low-latitudes intruded north. Due to this phenomenon, on July 25, zones with temperatures above −5°C were connected from the west to the east, but these were disconnected on the 26th. As Fig. 7 shows, an anticyclone itself was separated on the 30th. This anticyclone that was separated from the original anticyclones perished shortly after its separation and there were no further records of this anticyclone pattern for the year 2007. There were also no additional records showing the center of the anticyclones moving west to 120°E.

The formation and dissipation of the Shanxi Low
On July 25, a low pressure zone was reported that
formed a closed curved isobar of 5,820 gpm at 40°N, 100°E at 500 hPa. Since this was detected over Shanxi, China, it has been referred to as the Shanxi Low (Fig. 6). The pressure gradient force formed between this low pressure and the cold core anticyclone to the southeast attracted strong southerlies and led to the northward movement of relatively cold air lump. This low pressure was strong at 500 hPa but weak at 700 hPa and 850 hPa. In other words, this was a cold core low, not a thermal low, which is commonly found during these periods. Although they follow the westerly waves from India (not shown), they disappear over the plain of Tibet and then reappear again. Figure 7 shows the development of this low pressure from July 20, after crossing the plain of Tibet. It became a cut-off low on the 25th. Strangely enough, it remained stationed in the same location until August 2. It then moved eastward from

**Fig. 6.** The geopotential contours with wind vectors for July 25, 26, and 29 at 500 (high), 700 (mid.), and 850 hPa (low) using GDAPS data (Shaded: ≥−5°C).
Fig. 7. The equivalent potential temperature (Shaded: ≥327 K, Darker: ≥333 K) and geopotential height at 500 hPa from July 18 to August 15, 2007 (Except for July 22, 23, and 24 and August 9).
the 3rd in a nearly extinct state before disappearing completely from the analysis range on the 11th. On August 7, another trough came into this area from the west and continued until the 15th, so tropical air was accelerated to intrude north. In this case, regardless of the Shanxi Low, the creation was the result of Tropical Depression Pabuk (not shown), which formed over the East China Sea.

The formation and dissipation of the Baikal High

On July 28, a high pressure zone (Fig. 7, hereinafter referred to as the Baikal High) was established when closed curves at 5,880 gpm were detected for the first time over the region connecting Mongolia and Lake Baikal. As a typical warm core anticyclone, it was first formed at 700 hPa, and then spread to 500 hPa and 850 hPa (Fig. 6). Subsequently, it became completely stagnant and maintained its position over Primorsky Krai, Russia until August 11, disappearing from the area the next day. It had been stagnant over the Asian continent for 15 days.

Slowing down of the eastward movement

After August 10, a trough developed in the central region of China and generated continued southwesterlies over the Korean peninsula until the 15th. These southwesterlies were related, not only to the trough of mainland China, but also to a tropical cyclone over the East China Sea. In other words, tropical cyclone "PABUK" (the 6th typhoon of 2007) was the main reason that air was attracted from the southern equatorial regions to the mid-latitudes. Therefore, from the 11th to the 15th, rainfall during the day and tropical nights were detected, which is very uncommon during this time of the year. ("Tropical night" is an official term used in Korea to refer to a hot night with a minimum temperature above 25.) On the 13th, 14th, and 15th, a phenomenon presumed to be a tropical plume was detected. A jet stream (Fig. 11d) was connected to this cloud band. Though some of the convection activities that developed under the path of the jet stream were severe, they seemed to be the result of upper level divergence. The Knippertz example (2007) also contained two convections. We would like to call this cloud band a tropical plume. However, since these phenomena have never been reported during the summer in Asia, there are only speculations as to their existence, and their investigation is beyond the scope of this study, we would like to hand over the final decision to the next study.

In a nutshell, the reasons behind the continued rainfall from the end of the Changma season to August 15 can be summarized as follows. The generation of cold core anticyclones over the East China Sea and the development of the Shanxi Low in the northwest attracted strong southwestlies. These southwestlies pushed the tropical air north, which created the Baikal High. Then, this Baikal High, as well as the Shanxi Low and cold North Pacific anticyclone, remained stagnant, failing to move eastward, and causing the continuous rainfall. The existence of the dE, which caused the delayed eastward movement of the pressure system, can be explained as follows.

The Genesis and Movement of the Dry Equatorial Air Lump

The genesis of the dry equatorial air lump

Figure 1 represents the distribution of the variables that have typically been analyzed in previous studies on air masses. Here, 30°N represents the central region for the variables (Fig. 1b, d, and f). Figure 8 represents the cross section of this center. Southerly currents existed at the edges of the cold core anticyclone at 110°E and 150°E, and in the central position of the anticyclone, at 130°E, there were northerly currents that were colder and less humid than the surrounding air mass. In Fig. 8b, the omega (speed of ascend) and dew-point temperature are on opposite phases. This is because the region for descending air currents was dry. The low equivalent potential temperature can also be attributed to the dry environment. It was located over the ocean and was
even drier than T over land. The fact that the temperature was lower than T could make it E, but because it was even drier than E, we use the different term "dry equatorial air lump". If this phenomenon is repeated every year, we could use the term air mass. As the dE descended, it was influenced by the effects of an adiabatic lapse of increased temperature, and below 700 hPa it exhibited a higher temperature than its surroundings. In other words, it became a warm core anticyclone. As it is difficult to differentiate E below 700 hPa (Djuric, 1994), differentiating dE is more difficult. This is because of the abundant water vapor in the air and the high temperatures (Figs. 1c, g, and 8).

The movement of the dry equatorial air lump in the equivalent potential temperature field

The term dE refers to air that was drier than that of E. Figure 7 shows that dE was scattered over three zones. The first group existed in the inner regions of T, centered in low-latitudes, and the second group was scattered around the northern boundaries of warm and moist air in the mid-latitudes. The third group could be found in the Southern Hemisphere (some Figs are omitted). Here, the first group established its central point at 15°N, 150°E over the Northwestern Pacific on July 18, and gradually moved northwestward, expanding its area. On July 23, it detached itself from the center and moved to the East China Sea. On July 25, the center moved north beyond 20°N, merging with group 2 on July 26. The reason for the low value of equivalent potential temperature in this region is that the temperature and dew point temperature were lower than the surroundings. The difference in the dew-point temperature was larger than that for the temperature. The dE performed several westward movements. On July 18, groups 1 and 2 were found together. On July 20, these two groups merged. On July 25, group 3 to the east of 140°E began its westward movement. By July 30, group 4 was making its westward movement and merged with group 3 on August 2. The dE remained over the East China Sea until August 2, continually receiving supplementary force, before finally beginning to weaken and fade as it moved in a northeasterly direction. It continued its northeastern movement until August 13. From this point, it began to descend south and move westward on August 14. In other words, it rotated in a clockwise direction. It moved in a westward direction in the low-latitudes. It moved northward when approaching a continent. It moved eastward when confronting baroclinic waves in the mid-latitudes, and finally returned westward after penetrating deeply into the Pacific Ocean.

The equivalent potential temperature over Lake Baikal increased as the tropical and equatorial air ascended north from the Asian coastal areas from July 29. After that, the dE moved over Lake Baikal and into the Siberian regions to the north, moving into the extreme north on July 31 and August 1. On August 7, we can once again find the northward intrusion of a moist air mass from the south with the remaining forces of the dE already moving into the northern regions. This northward intrusion penetrated through the Korean peninsula and headed toward Manchuria and the North Pole. When it began fading again, it went out through the east of the Korean peninsula on August 11.

On August 7, when the moist air mass intruding northward faded and diminished in the high-latitudes, the center of the dE rotated around the island of Japan. The center of the dE transferred to the ocean around Ogasawara, south of Honshu, Japan on August 8, and began its northern movement on August 11. It reached Hokkaido and descended south on August 13, and once again returned to the ocean around Ogasawara on August 15.

The changes in the equivalent potential temperature at 850 hPa (Fig. 9) only indicate that the guessed center of the E was located farther to the north on August 15 (assumed to be over north to Korea and Japan) than on July 18 (assumed to be over Ogasawara), while providing no evidence to explain the difference in movement between a dE and E. This proves that it is difficult to differentiate between E and T in the low levels of the troposphere (Djuric,
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1994). This reinforces the importance of the equivalent potential temperature distribution at 500 hPa in weather forecasting during this season.

Fig. 8. (a) The cross section of wind vector, temperature, and dew-point temperature (Shaded: ≤−15°C) at 30°N, (b) Zonal distribution of temperature, dew point, equivalent potential temperature, and omega on the axis of 30°N at 500 hPa on July 28, 2007.

Fig. 9. The equivalent potential temperature (Shaded: ≥327 K, Darker: ≥333 K) at 850 hPa for July 18, 25, and 29 and August 11 and 15 from left.

The movement of the dry equatorial air lump in the precipitable water field Because precipitable water increases in the presence
of ascending currents according to convergence, it is difficult to differentiate air masses using this value, but in regions with no convergence, it provides a clear indication of the dryness of the air mass (Reber and Swope, 1972; Wei et al., 1999). The low precipitable water signifies that the lower levels were also very dry. Figure 10 clearly shows that the dE area was not only dry at 500 hPa, but at lower levels as well. On July 25, the southern and eastern coastlines of China, representing a dry region of 3-4 cm precipitable water, were surrounded by a moist region of over 4 cm of precipitable water.

This dry region provided two operations. First, the areas surrounding this descending divergent current attracted a convergent ascending current. Therefore, this dry region was always surrounded by moist regions. In addition, during the entire analysis period, these induced moist regions dominated over the Korean peninsula (some figures are omitted). In other words, the long continuous rainfall in early August was the direct result of these convergent ascending currents surrounding the dry descending currents. Second, the induced southerlies to the west of this dry region induced the northward intrusion of low-latitude air masses and lumps. Here, a phenomenon generally not induced by the North Pacific anticyclone was produced by the dE. Because of this, the Shanxi Low could not move eastward and faded in a stationary location. On July 29, the dE began its westward movement from 25°N, 160°E (falling under group 4 in

**Fig. 10.** The distribution of precipitable water (Shaded: ≥4 cm, Darker: ≥5 cm) on July 25, 26, 28, 29, 30, 31 and August 1, 10, 11, 12, 13, 14, 15 from left.
Fig. 7. It then intruded northward, moved eastward, and finally descended to the southern coastal areas of Japan on August 15.

Amplification of the low-latitude easterly belt force

The central force of the low pressure over Manchuria that was present on July 18 finally faded off the analysis domain of the study on August 10 (Fig. 7). It had remained stagnant in the same region for 24 days. There are two reasons why it failed to move eastward from the westerly waves in the region. First, the anticyclone centered on the eastern ocean of Japan was a semi-stagnant one. It remained stagnant within the region during the entire summer at 500 hPa. Second, as has already been investigated in relation to the equivalent potential temperature field, there was a wave that continuously moved eastward within the North Pacific anticyclone south of 40°N. When the force of the westerly waves moving eastward is weak, the easterly waves intrude deep into the high-latitudes, and in 2007 there was a comparatively very high ascendance of this phenomenon.

From August 11, a new unique phenomenon was detected. A long wave trough at coordinates (50°N, 110°E) within the domain of Fig. 7 produced a retrogression phenomenon seen in a short wave trough until August 15 and established a low-pressure center over Mongolia on August 15. This current moving eastward from the west of this low pressure suddenly descended south and penetrated into Hainan, China.

Under these conditions, tropical cyclone “PABUK” positioned itself over the West Sea of the Korean peninsula (Fig. 11a), inducing a huge amount of the humidity present in the E to move north (Fig. 11b), thus causing continuous rainfall around the Korean peninsula. Through this, the cloud bands stretching from the low-latitudes into the high-latitudes formed the pattern shown in Fig. 11c, along with the jet stream (Fig. 11d), causing the tropical nights and the continuous rainfall over the Korean peninsula to last until August 15.

The Evolution of the Dry Equatorial Air Lump

Definitions of an equatorial air mass and a dry equatorial air lump

Figure 12 represents the effort that went into seeking a method to analyze a dE by comparing E and T. The term dE refers to a dry descending air current within the moist air mass of E or T. Through trial and error, we decided upon the boundary values used to represent the dry regions shown in Fig. 1d. First, we distinguished between E and T based on temperature. If −4.5°C was set as the boundary, every part of East Asia was represented as E. In contrast, when we used −5.5°C as the boundary, the majority of E disappears. If E is the result of a relative shortage of sunlight at the equator and in the winter hemisphere, it is reasonable to a certain degree to establish these differentiated domains. Therefore, the
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most suitable boundary between E and T is $-5.0^\circ C$. In lower layers below 700 hPa, this classification cannot be seen clearly. The boundary between E and dE was selected as the value that most similarly represented the dry regions in Fig. 1d under a 330.5 K equivalent potential temperature. If the value is greater, the domain of the dE becomes too broad, and if it is lower, it becomes too narrow. Therefore, we chose the middle picture, and Table 2 was produced based on these findings. Regions with less than 3 cm of precipitable water were excluded from the analysis, thus preventing mid-latitude humid zones from being classified as T.

Evolution of a dry equatorial air lump

E began its first northward intrusion from 120°E on July 18, passing 20°N. On July 26, it penetrated the wall of T, which blocked this northward intrusion. Figure 14 represents the estimated dates for the center of the E, and the dE for this period is represented by Fig. 13. Here, both the E and dE intruded north simultaneously. Both the E and dE, which intruded north until it reached 40°N, continued their movement in an eastward direction, and from July 30, they moved southward. After July 31, they remained for a long time over the East China Sea in the form of a dE. On August 3, the northward intruding E and the
Fig. 13. The classification for Equatorial (E: Light gray), dry-Equatorial (dE: Gray), and Tropical (T: Dark) air masses following Table 2 (except for precipitable water) at 500 hPa from July 18 to August 15, 2007 (Except for July 22, 23, and 24 and August 9).
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stagnant dE joined together. These joined air masses once again penetrated through the wall of T in the mid-latitudes on the 4th. During this second intrusion, the path of northward intrusion shifted eastward to 140\(^\circ\)E by 20\(^\circ\)E. The northward invading E and dE reached as far north as 60\(^\circ\)N on August 8, moved eastward, began a southward movement, and arrived over the southern coast of Japan on August 11.

During these two rotations, the E and dE always moved together. During the third rotation on August 12, only the dE moved. It began from the eastern seas of Hokkaido, Japan, reached the Northwestern Pacific, and rotated back to the southern coastal areas of Japan. This period was when the boundaries of the E, T, and dE were continuously transferred near the Korean peninsula and rotated around the Northwestern Pacific, thus functioning as the reason for the continuous rainfall during this period. The east-west current greatly decreased while the south-north currents strengthened. And a phenomenon similar to a tropical plume was established.

Until today, the summer rainy season in East Asia (Changma, Meiyu, and Baiu) has been understood to occur at the boundaries between tropical and polar air masses. However, there were no signs of a polar air mass after the end of the Changma period, thus reconfirming the fact that T, E, and dE were the major cause of the continuous rainfall in the summer of 2007.

### Summary and Conclusion

While investigating the reasons for the unique phenomenon of continuous rainfall after the Changma period in 2007, the following phenomena were found. First, a northward intrusion of relatively cold air from the low-latitudes was found. These cold air masses were defined as E, which intruded northward from the low-latitudes, rotated twice over the Northwestern Pacific, and remained in this area for 12 days. Second, the E did not move alone, but moved with a very unique air lump called a dE. Third, the E and dE rotated in clockwise sense for a prolonged period of time and almost stagnant at other times. In addition, the North Pacific anticyclone remained stagnant so the easterlies prevail over the western Pacific.

In the mid-latitude regions with westerlies prevailing two facts are notable. The first was the development of a low pressure over Shanxi, China. A cold core low moved from the west became weak while passing the Tibetan plateau, regenerated itself over Shanxi, and caused strong southerlies to the southeast of its center position. After this, it lingered at that position for a while and at last diminishes completely. The development of the Shanxi Low occurred twice during the analysis period and the two instances showed similar patterns and behaviors. Because of this, continuous rainfall over the Korea peninsula occurred for 12 days after the end of the Changma period between the E and T, as well as between the E and mid-latitude air masses. Second is the fact that the high pressure above Lake Baikal was created by the northward intrusion of the equatorial air and remained stagnant for a prolonged period of time. This blocked the east-west current, thus forming the foundations for the continued rainfall over the Korean peninsula. In addition to these five findings, between August 12 and 15, low-latitude air from the south penetrated deeply into the north, reaching 60\(^\circ\)N, due to a tropical cyclone, thus bringing rainfall during the day and tropical nights, which can also be considered as one of the reasons for the continuous rainfall on August 15.
One of the fundamental reasons behind the rise of these phenomena could be the dE, which was a dry descending air current from the higher levels of the Northwestern Pacific. It moved westward between 20-40°N and performed a rotational eastward movement in the mid-latitudes, always accompanied by E, thus being considered as one of the reasons for the summer climate change. The North Pacific anticyclone remained stagnant over the western regions of 150°E, thus only the E and dE rotated in the regions to the west of the North Pacific anticyclone. This kind of northward intrusion of E had not been detected in the past 10 years.

In addition to investigating the reasons behind the continuous rainfall after the end of the Changma period, this study had other accomplishments. First, we successfully redefined the E and T theory to meet the Asian environment. At the same time, we found a definition for a dE, the unique descending current (Table 2) that was detected during the study period. In this case, it was limited to cases with precipitable water greater than 3 cm. These boundary values are different from those presented by Baum et al. (1997) and Jahn (2007), which were used in the Atlantic region.

Second, we confirmed the genesis and development process of dE: dE was a descending divergent current, created in a high pressure area of the North Pacific, and the boundaries were responsible for expanding the sphere of E. When it ascended north into higher latitudes, it created a convergence and precipitation regions, and tended to transform according to the increased temperature of the mid-latitude region after the northward intrusion.

In summary, there were active northward intrusions of warm and moist air from low-latitudes, accompanied by the eastward movement of the pressure system being blocked. It was found that these unique phenomena were due to a very special atmospheric circulation, the northward intrusion of a dE. In addition, it is also difficult to conclude whether the dE analyzed in this study was unique to the year 2007 or occurred in past years. However, due to its impact in creating a unique and catastrophic weather change, there is a strong need to conduct further studies in this field.

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