This is a PDF of a manuscript that has been peer-reviewed and accepted for publication. As the article has not yet been formatted, copy edited or proofread, the final published version may be different from the early online release.

This pre-publication manuscript may be downloaded, distributed and used under the provisions of the Creative Commons Attribution 4.0 International (CC BY 4.0) license. It may be cited using the DOI below.

The DOI for this manuscript is
DOI:10.2151/jmsj.2020-035

J-STAGE Advance published date: May 26th 2020

The final manuscript after publication will replace the preliminary version at the above DOI once it is available.
Unusual Characteristics of Extratropical Transition of Typhoons in August 2016

Nao TAKAMURA

Disaster Prevention Investigation Department
Tokyo District Meteorological Observatory, Tokyo, Japan

and

Akiyoshi WADA

Department of Typhoon and Severe Weather Research
Meteorological Research Institute, Tsukuba, Japan

February 10, 2019
Revised March 19, 2020

1) Corresponding author: Nao Takamura Tokyo District Meteorological Observatory, 3-235, Nakakiyoto, Kiyose, Tokyo 204-8501, Japan.
Email: n_takamura@met.kishou.go.jp
Tel: +81-42-497-7217
Fax: +81-42-495-3180
Abstract

In August 2016, a total of eight typhoons formed in the western North Pacific, and four of which landed on northern and eastern Japan. These typhoons were associated with heavy rainfall and strong winds and caused massive damages in the Japanese archipelago. Moreover, five of the eight typhoons underwent extratropical transition (ET), which was more frequent than an average of 2.1 typhoons per year during August. To clarify the characteristics of the typhoon tracks that caused such unusual landfall and frequent ET in August 2016, we conducted $k$-means cluster and cyclone phase space (CPS) analyses for typhoons that occurred in August and September. Composite analysis and case study were also conducted to clarify the synoptic environments around the typhoons. To examine the unusual characteristics in August 2016, we compared the results of the analyses for this period with those in August from 2001 to 2015 and those in September 2016. The $k$-means cluster analysis showed that the direction of the typhoon tracks in August 2016 were more northward than that of the typhoons in August from 2001 to 2015 and those in September 2016. Moreover, the CPS analysis revealed that ET in August 2016 was characterized by a more indistinct structural change from a warm-core structure to a cold-core structure with a shorter duration than ET in August from 2001 to 2015. The synoptic environments around the typhoons in August 2016 were characterized by enhanced undulations of the upper-tropospheric jet stream, increased amplitudes of the mid-tropospheric trough, and
relatively warm air around the typhoons in the lower troposphere. These synoptic
environments explained the unusual landfall of typhoons with a more northward track and
the more frequent ET and more indistinct structural evolution of ET in August 2016.

**Keywords** extratropical transition; typhoon track; k-means cluster analysis; cyclone phase
space; synoptic environment
1. Introduction

In the middle latitudes of the western North Pacific, typhoons often undergo structural transformation. Extratropical transition (ET) is the process that is associated with the transformation of a tropical cyclone to an extratropical cyclone in a baroclinic environment and the reduction in sea surface temperature (SST) at high latitudes (Evans et al. 2017). From 1981 to 2010, the average number of typhoons that formed in the western North Pacific per year was 25.6; among these typhoons, 10.9 underwent ET. The data for the month of August within the time frame indicated an average of 5.2 typhoons per year, with 2.1 typhoons per year undergoing ET. However, in August 2016, eight typhoons formed in the region, and five of which underwent ET (Fig. 1). Moreover, four typhoons landed in Japan, and three of which landed in Hokkaido. This was the first in the history of the region’s meteorological data (JMA 2017; https://www.jma.go.jp/jma/kishou/books/saigaiji/saigaiji_201701.pdf). The heavy rainfall and strong winds that associated these typhoons caused massive damages from eastern Japan to northern Japan. Kanada et al. (2017) reported this unusual pattern of typhoon landfall over eastern Hokkaido in northern Japan (from the Pacific) in August 2016.

A series of observations and numerical experiments have been dedicated to the study of the ET phenomenon (Jones et al. 2003; Evans et al. 2017). The JMA (1990) classified the ET process into three categories from an operational point of view: (a) an intense typhoon circulation, (b) a weak typhoon merged with an extratropical cyclone, and
(c) an ET under the conditions of weak baroclinicity and low SST. Jones et al. (2003) and Evans et al. (2017) provided instructive reviews on the climatology and physical process of ET. For instance, the climatological features of ET have been investigated in several basins, such as the Atlantic basin (Hart and Evans 2001) and the western North Pacific (Kitabatake 2011). These studies have collectively suggested that the location and seasonal evolution of ET are due to the relationship between SST and baroclinic growth.

Regarding the structural evolution of ET, Muramatsu (1982) explained the five physical processes of ET that were associated with westerlies in the case of Typhoon Owen (1979) based on in-situ observations: (1) asymmetrization in lower temperature, (2) loss of deep convection around the tropical cyclone (TC) center, (3) loss of warm-core of the TC center, (4) poleward shift and asymmetrization of precipitation area, and (5) loss of circulation of the TC center and intrusion of dry air into it in the middle layer of the atmosphere. Zhong et al. (2009) found that the evolution process of ET in the warm season (June to September) could be classified into two types: (a) a weak baroclinic feature in low latitudes and (b) an interaction between a TC and an upper-level mid-latitude trough when the TC either approached or was absorbed into the trough. During the cold season (October to May), there was only one evolution process, and this process was similar to the interaction between a TC and an upper-level mid-latitude trough.

Reanalysis data have been frequently used to investigate the ET process (Klein et al. 2000; Sinclair 2002; Hart et al. 2006). Klein et al. (2000) divided the process into
transformation and reintensification stages and proposed a three dimensional conceptual model of the transformation stage. Sinclair (2002) and Hart et al. (2006) investigated the transformation process from axisymmetric TCs to asymmetric extratropical cyclones. The nature of ET evolution and intensity change was sensitive to the space and time scales of the interaction between a trough and a TC (Hart et al. 2006). Furthermore, Hart et al. (2006) showed that a negatively (positively) tilted 500 hPa large-scale trough was advancing on the TC in cases of intensification (decay) after ET completion. Kofron et al. (2010) investigated the interaction using isentropic potential vorticity (IPV) on the 330 K potential temperature isentropic level and concluded that a 330 K IPV was a good discriminator for examining ET of TCs: a 330 K IPV increased dramatically when TCs entered mid-latitude environments and then underwent ET, whereas a 330 K IPV did not increase when TCs did not interact with mid-latitude environments or when TCs dissipated after ET. From the perspective of frontal evolution, Kitabatake (2008a) examined the difference in the characteristics by classifying ET cases in the western North Pacific from 2001 to 2002 into three categories: (a) warm secluded frontal and subsequent occluded patterns, (b) absorption into vigorous preexisting fronts (cold advection), and (c) organization into open-wave frontal cyclones.

One of the metrics for defining ET is a cyclone phase space (CPS). Hart (2003) proposed a CPS analysis method that was composed of a few parameters in a diagram. The diagram can represent the life cycle of a cyclone, including the onset and completion of
ET (Evans and Hart 2003). Furthermore, Arnott et al. (2004) conducted a CPS analysis for a representative of seven clusters obtained via a $k$-means cluster analysis (MacQueen 1967) for hurricanes in the North Atlantic basin from 1998 to 2002. The seven clusters included three clusters on a TC, two clusters on a transition/hybrid type, and two clusters on an extratropical cyclone. Arnott et al. (2004) determined a representative mean path in the CPS diagram via the stages of ET.

In August 2016, typhoons underwent ET more frequently, that is, the ratio of the number of ET cases to that of typhoons was higher (62.5%) in August 2016 than in August from 2001 to 2015 (average: 41.3%, standard deviation: 20.6%) (Fig. 2a). The frequent ET was also observed in September 2016, where the ratio of ET cases was higher than that in September from 2001 to 2015 (Fig. 2b); however, the difference was not significant unlike August. Kitabatake (2011) showed that the frequency of typhoons was highest in August from 1979 to 2004, whereas that of ET cases was highest in September from 1979 to 2004. Hart and Evans (2001) showed that the monthly frequency of ET in the Atlantic basin correlated well with the monthly number of TCs and that the probability of ET was highest in September and October. However, in 2016, the frequency of both typhoons and ET cases was highest in August. Furthermore, typhoons landed in Japan more frequently in August 2016. The comparison of typhoon tracks revealed a distinct difference for August and September in 2016 (red lines in Fig. 1) although there was no clear difference for these two months from 2001 to 2015 (blue lines in Fig. 1). The relationship between the
characteristics of ET and the differences in typhoon tracks for August and September 2016 is important for understanding the frequent and unusual landfall of typhoons in Japan in August of the same year. The present study aims to specify the characteristics of (1) the track that causes the frequent landfall and ET of typhoons and (2) the synoptic environment around these typhoons in August 2016. This study presents representative typhoon tracks by using \( k \)-means cluster analysis, shows the structural evolution of typhoons on the basis of CPS analysis, and extracts the characteristics of synoptic environments from composite analysis and case study for typhoons in August and September from 2001 to 2016.

The rest of this paper is outlined as follows. Section 2 describes all data and methods used in this study. Section 3 presents the study results. Section 4 provides the discussion and a summary of the general findings of the paper.

2. Data and Method

To specify the characteristics of ET in August 2016, we compared the characteristics of typhoons in August 2016 with those in August from 2001 to 2015. We also compared the characteristics of typhoons in August 2016 with those in September 2016 to understand the relationship between the characteristics of ET and the difference in typhoon tracks for August and September 2016.

Typhoon data such as latitude, longitude, and central pressure were taken from the best track data archives of the Regional Specialized Meteorological Center (RSMC) Tokyo
(http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html). Two kinds of Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) products performed by the Japan Meteorological Agency were used according to the research purpose. Calculations of the CPS parameters (see Section 2.1), the composite analysis, and the case study of synoptic environments were conducted with the six-hourly JRA-55 data with a horizontal resolution of 1.25° × 1.25°. Monthly JRA-55 data with the same horizontal resolution were also used to show the monthly mean atmospheric distributions. Distributions of the monthly accumulated precipitation were calculated on the basis of the hourly global precipitation dataset obtained from the Global Satellite Mapping of Precipitation (GSMaP) version 7 (Okamoto et al. 2005; Kubota et al. 2007; Aonashi et al. 2009; Ushio et al. 2009).

The focus of the case study was Typhoon Chanthu (T1607) in August 2016. For comparison, Typhoon Meranti (T1614) in September 2016 was equally studied. T1607 formed south of Japan at 1800 UTC on 13 August, moved northeastward, and then reached its maximum intensity at 0000 UTC on 16 August before eventually moving northward. For the purposes of this study, the maximum intensity (Max) is defined as the time of occurrence of the lowest central pressure before the onset of ET (TB; see Section 2.1). Apparently, T1607 underwent TB at 0600 UTC and completed ET (TE; see Section 2.1) at 1200 UTC on 17 August while moving northward from the Kanto region to the Sanriku Coast. The duration of ET from TB to TE was six hours. Meanwhile, T1614 formed south of
Japan at 0600 UTC on 10 September, moved northwestward, reached its Max at 1200 UTC on 13 September, and landed in south China before undergoing TB at 1200 UTC on 15 September and TE at 0000 UTC on 17 September. The duration was 36 hours, which was six times longer than that with T1607.

The principal methods used in the study, namely, CPS analysis and k-means cluster analysis, are described in detail in the next sections.

2.1 Cyclone phase space analysis

A CPS diagram have three parameters: $B$, $-V_T^L$, and $-V_T^H$ (Hart 2003). $B$ represents the asymmetry of the storm-motion-relative thickness. $-V_T^L$ represents the vertical derivative of the horizontal gradient calculated between 600 and 900 hPa geopotential heights. $-V_T^H$ represents the vertical derivative calculated between 300 and 600 hPa. The parameter associated with the thermal wind relationship indicates whether the storm has a cold- or warm-core structure. In the present study, $B$ and $-V_T^L$ were calculated using geopotential height distribution within a 500 km radius from the typhoon center. The onset and completion of ET were determined on the basis of the following definitions (Evans and Hart 2003):

- Onset of ET (TB): occurs at the time when the value of $B$ exceeds 10
- Completion of ET (TE): occurs at the time when the value of $-V_T^L$ becomes negative

The calculation domain was based on the typhoon center obtained from the best
track data. The horizontal resolution of JRA-55 data (1.25° × 1.25°) was coarse relative to that of the best track data (~0.1°). The data grid had an asymmetric distribution relative to a circle that depended on the position of the typhoon center. To reduce error, the cyclone parameters were calculated using linearly interpolated JRA-55 data with a 0.25° horizontal resolution.

2.2 K-means cluster analysis

K-means cluster analysis has been widely used for TC analysis (e.g., Arnott et al. 2004; Elsner and Liu 2003). Elsner and Liu (2003) used a $k$-means cluster analysis to separate typhoons into three clusters on the basis of the position of the typhoon center at the maximum intensity and at the final intensity. In the present study, the latitude and longitude in the best track data were time averaged for each typhoon in the zonal and meridional directions, respectively, to create a set of tracks of equal length for each typhoon. An optimal number of clusters must be selected in the $k$-means cluster analysis. In this study, $k$-means cluster analysis was applied for typhoons in August and September from 2001 to 2016. Thus, we conducted several $k$-means cluster analyses by using the different number of clusters. With trial and error, four clusters were obtained from the analyses, which were subsequently utilized for investigating the typhoons in August 2016.
3. Result

3.1 Results of clustering and CPS analysis

To understand the characteristics of ET in August 2016, we compared the typhoons that formed during this period with those in August from 2001 to 2015. A closer look at the annual number of ET cases validated ET frequent in August 2016 (Fig. 2a). In Fig. 1a, many typhoons moved northwestward, changed their direction around Japan and south of Japan, and then moved northeastward. Some typhoons continued northwestward and eventually landed on the Asian Continent. Some typhoons in August 2016 moved more northward than those in August from 2001 to 2015 (Fig. 1a).

The $k$-means cluster analysis (Section 2.2) produced four representative clusters (Fig. 3) that had the following individual characteristics:

(i) Cluster1 (the NE cluster; NE indicates northeastward movement):

The typhoons in this cluster formed east of the Philippines, changed their movement direction south of Japan, and then moved northeastward. Moreover, these typhoons underwent ET as they approached the Japanese archipelago and then moved northeastward.

(ii) Cluster2 (the N cluster; N indicates northward movement): The typhoons in this cluster formed southeast of Japan and then changed their movement direction. Some typhoons moved northeastward, and the others moved northward. These typhoons underwent ET east of Japan.
(iii) **Cluster3 (the W cluster; W indicates westward movement):** The typhoons in this cluster formed near the Philippines, moved westward, and underwent ET near the Philippines and the South China Sea.

(iv) **Cluster4 (the NW cluster; NW indicates northwestward movement):** The typhoons in this cluster formed east of the Philippines, moved northwestward, and underwent ET over the ocean from the East China Sea to the Yellow Sea.

The direction of the typhoon tracks was more northward in the NE and N clusters in 2016 than that from 2001 to 2015 (Figs. 3a, b), whereas there was no distinct difference in the typhoon tracks in the W and NW clusters (Figs. 3c, d). Table 1 shows the mean positions (latitude and longitude) of the typhoon center at Max, TB, and TE in August 2016 and in August from 2001 to 2015. The mean latitudinal positions were more northward in August 2016 than in August from 2001 to 2015, and the mean longitudinal positions were more eastward in August 2016 than in August from 2001 to 2015. In most cases, the movement speed of the typhoons became faster after TE than before TB when they moved either northwestward or northeastward (Fig. 4). Moreover, the movement speed of the typhoons in August 2016 was faster than that of the typhoons in August from 2001 to 2015 when they moved northward. The difference in the movement speed in August 2016 from that in August from 2001 to 2015 could be closely related to the difference in the mean positions shown in Table 1.
The CPS diagrams obtained from the CPS analysis described in Section 2.1 are shown in Figs. 5a and b. Each panel includes a trajectory for all ET cases (brown and gray lines) and mean trajectories (red and black lines) between 72 hours before TE (TE-72h) and 72 hours after TE (TE+72h) in August 2016 and in August from 2001 to 2015, respectively. Meanwhile, the time series of the mean parameters used in the CPS analysis (Section 2.1, red and blue lines), together with those of the mean central pressure (green lines) between TE-72h and TE+72h in August 2016 (circles) and in August from 2001 to 2015 (diamonds), respectively, are displayed in Figs. 6a and b. The CPS diagram revealed a structural change from a warm-core symmetric structure (TC; fourth quadrant) to a cold-core asymmetric structure (extratropical cyclone; second quadrant). Furthermore, the structural change to the cold-core structure in August 2016 was not as distinct compared with that in August from 2001 to 2015 (Figs. 5a, b and red circles in Figs. 6a, b). The composite analysis has shown that although there was no clear difference, the central pressure in August 2016 was higher than that in August from 2001 to 2015, thus indicating that the typhoons in August 2016 were relatively weak (green circles and diamonds in Fig. 6). The duration of ET from TB to TE in August 2016 was either equal to or shorter than 6 hours (average: 3.6 hours; standard deviation: 2.9 hours), which was significantly shorter than that in August from 2001 to 2015 (average: 28.7 hours; standard deviation: 20.5 hours). Approximately 80% of the ET cases in August from 2001 to 2015 had a duration longer than 6 hours. On this regard, it should be noted that a duration in this context is set to “zero”
when a typhoon simultaneously undergoes TB and TE.

According to the $k$-means and CPS analyses, the typhoons in August 2016 tended to have specific characteristics such as more northward typhoon tracks and positions at TE, faster movement, shorter ET duration, and more indistinct structural change to the cold-core structure. The following section addresses the question of whether such characteristics are related to the synoptic environments around these typhoons.

3.2 Synoptic environments

As explained in Section 2, a case study for T1607 is helpful for understanding the roles of synoptic environments in characterizing typhoon tracks and ET in August 2016. The duration of ET from TB to TE in the case of T1607 was six hours. Thus, we compared the horizontal distributions at TB and TE with the composite maps at TE-6h and TE in August from 2001 to 2015.

A 500 hPa geopotential height was selected to help understand the roles of a mid-tropospheric trough in ET. This height was determined as the steering-flow level in general. Figure 7 shows the comparison of the horizontal distributions of the 500 hPa geopotential height in T1607 (Figs. 7a, b) with the composite maps in August from 2001 to 2015 (Figs. 7c, d). The center of the domain is located at the typhoon center in each panel in Fig. 7. A negatively tilted (north–northwest to south–southeast oriented) mid-tropospheric trough on the northwest of the typhoon center approached the typhoon at TB (Fig. 7a) and
then merged with the typhoon at TE (Fig. 7b) in August 2016. These characteristics were similar to those averaged from 2001 to 2015 (Figs. 7c, d). Nevertheless, the amplitudes of the trough more increased in August 2016.

The role of upper-level synoptic environments in an extratropical development during ET has been discussed with Hurricane Iris (1995) (Thorncroft and Jones 2000). The conceptual model of the transformation stage of ET of Klein et al. (2000) streamlined the importance of a polar jet at a 300 hPa level. With reference to Klein et al. (2000), the present study addressed the 300 hPa level for examining an upper-tropospheric jet stream. The typhoon in August 2016 approached and merged with an upper-tropospheric jet stream at TE (Figs. 8a, b). Therefore, the characteristics of the typhoon in August 2016 were similar to those averaged in August from 2001 to 2015 (Figs. 8c, d). Nevertheless, the undulations of the jet stream were more enhanced in August 2016.

A baroclinicity in the lower troposphere was examined using a 850 hPa temperature (Fig. 9). Relatively cold air flowed northwest of the typhoon center in the lower troposphere in August 2016 (Figs. 9a, b). The characteristics in August 2016 were similar to those averaged in August from 2001 to 2015 (Figs. 9c, d). Nevertheless, the air around the typhoon in the lower troposphere was relatively warm in August 2016.

3.3 Differences for August and September in 2016

The typhoon tracks in August 2016 were significantly different from those in
September 2016 (Fig. 1). Figure 10 shows the distributions of the monthly accumulated precipitation in August and September 2016, which are based on the GSMaP dataset (see Section 2). The areas of heavy precipitation were closely associated with the typhoon tracks. These areas of heavy precipitation expanded north–south in eastern and northern Japan in August 2016 (Fig. 10a), and east–west in western Japan in September 2016 (Fig. 10b). Thus, both distributions of the typhoon tracks and the monthly accumulated precipitation were significantly different for the two months. In this section, the characteristics of the typhoons in August and September 2016 are compared, and the differences are specified.

As indicated by the cluster analysis, half of the eight typhoons in August 2016 fell under the NE cluster, five ET cases were under the NE and N clusters, and one case was under the W cluster. Collectively, the cases in August 2016 were mainly under the NE cluster. The six typhoons in September were only under the W and NW clusters. Therefore, there was a significant difference in the clusters associated with the typhoon tracks in August and September 2016, whereas there was no distinct difference for these months from 2001 to 2015 (Fig. 1).

On the other hand, there was no distinct difference in the results of the CPS analysis in August and September 2016 (Figs. 5, 6). This finding suggests that the difference in the typhoon tracks in the two months could be closely related to the differences in synoptic environments. A comparison of the synoptic environments for T1607 in August 2016 and for
T1614 in September 2016 are presented as follows.

According to the 500 hPa geopotential height in T1607, the increased amplitudes of a negatively tilted trough approached the typhoon (Figs. 7a, b), whereas the 500 hPa geopotential height was almost zonal in T1614 (not shown). For the 300 hPa zonal wind, the undulations of the upper-tropospheric jet stream were enhanced in T1607 (Figs. 8a, b) but were not clear in the case of T1614 (not shown). However, the typhoon existed near the entrance of the jet stream at TB and merged with the jet stream at TE in both typhoon cases. From the 850 hPa temperature, cold air flowed gradually into the northwest of the typhoon center, but the air around the typhoon was relatively warm in both T1607 (Figs. 9a, b) and T1614 (not shown). Moreover, in T1614, the north–south temperature gradients were enhanced around the typhoon center at TE. These characteristics of synoptic environments have also been observed in the composite maps in August 2016 (Fig. 11).

On the basis of the results of the comparisons for August 2016 and August from 2001 to 2015 and for August and September in 2016, Fig. 12 displays a good summary of the synoptic environments in August 2016. First, the undulations of the upper-tropospheric (300 hPa) jet stream were enhanced, and the amplitudes of the mid-tropospheric (500 hPa) negatively tilted trough increased. Then, both the jet stream and the trough merged with the typhoon. Furthermore, the relatively warm air existed around the typhoon in the lower troposphere (850 hPa). Hart et al. (2006) indicated that a negatively tilted trough caused the intensification of a storm after ET, wherein the associated mechanism was supposedly
a concentration and an intensification of eddy potential vorticity (PV) flux. The synoptic environments indicated in the present study resulted in the northward typhoon tracks, frequent ET, and indistinct structural change to the cold-core structure.

4. Discussion and Summary

4.1 Discussion

A discussion of the unusual characteristics in August 2016 (Section 3) is important. On this regard, it is imperative to consider the horizontal distributions of the monthly mean 500 hPa geopotential height (Fig. 13a) and monthly mean 850 hPa temperature (Fig. 13b) in August 2016 with their anomalies deviated from the monthly mean for the period of 1981 to 2010. The 500 hPa geopotential height was high around the areas far east of Japan and from northeast China to the Korean Peninsula. A trough existed west of Japan between these high areas (Fig. 13a), thus indicating that typhoons in August 2016 moved northward east of Japan along the western edge of the subtropical high and then underwent ET upon interaction with the trough at relatively high latitudes. Furthermore, moist air in the lower troposphere was transported from the Pacific side of eastern Japan to northern Japan along the western edge of the high (Fig. 13b). The transport of moist air helped maintain the warm-core structure of typhoons traveling over relatively high latitudes in August 2016; therefore, the CPS analysis showed an indistinct structural evolution compared with that averaged from 2001 to 2015.
Next, the comparison of the typhoon tracks with the distributions of the monthly accumulated precipitation in 2016 (Figs. 1, 10) suggested that the areas of heavy precipitation were closely associated with the typhoon tracks. From the composite analysis, Atallah et al. (2007) indicated that in the cases of ET, the precipitation shifted to the left of the track of the transitioning TC. The precipitation area shifted north–northwestward of the TC track when a positively tilted mid-latitude trough approached the TC. On the other hand, TCs that had precipitation on the right side of the track interacted with a downstream ridge. Atallah and Bosart (2003) reported that the precipitation shifted to the left side of the track of Hurricane Floyd (1999). The juxtaposition of a cold-core PV anomaly associated with the mid-latitude trough and a warm-core PV anomaly associated with Floyd played a role in creating a strong and deep tropospheric baroclinic zone. This baroclinic zone provided a region that is favorable for a deep isentropic ascent when the circulation of Floyd approached the coast, thus resulting in prolific precipitation. Shimazu (1998) characterized typhoons approaching mid-latitude frontal zones by delta-shaped prominent precipitation systems called delta rain shields. Kitabatake (2008b) diagnosed Typhoon Tokage (0423) which associated with heavy rainfall on the left side of the typhoon. Tokage was located in the right entrance of an upper-tropospheric jet streak and in the downstream of an upper-tropospheric weak trough. It eventually transformed into a frontal cyclone in the baroclinic zone. This approach of Tokage to the upper-tropospheric jet stream and the lower-tropospheric air on the cooler side of the frontal-zone over the warm sea surface was
considered to have contributed to the heavy precipitation on the left side of the typhoon track. In August 2016, the undulations of the upper-tropospheric jet stream were enhanced, and the amplitudes of the mid-tropospheric trough increased at high latitudes, with the air around the typhoon in the lower troposphere being relatively warm. As a result, the typhoons moved northward while maintaining a warm-core structure and then underwent ET at high latitudes. Therefore, the areas of heavy precipitation expanding north–south were found ahead of the typhoon where frontogenesis occurred owing to the increased amplitude of the trough. In September 2016, the undulations of the jet stream were not clear and were located at relatively low latitudes, and the amplitudes of trough decreased. Moreover, the typhoons had relatively enhanced north–south temperature gradients in the lower troposphere and underwent ET. These characteristics were relatively consistent with those shown by Shimazu (1998) and Kitabatake (2008b). Therefore, the areas of heavy precipitation expanding east–west were found ahead of the typhoon owing to the enhanced north–south temperature gradients. In this context, it is necessary in the future to explore the relationship between the precipitation distribution and individual typhoon track and to discuss synoptic environments that would determine the precipitation distributions.

4.2 Summary

The meteorological data in Japan indicated that there was a more frequent ET in August 2016 than in the same month from 1981 to 2010. To elucidate such unusual
characteristics of the typhoon in August 2016, this study explored and compared the characteristics of the typhoons in August 2016 with those in August from 2001 to 2015 and with those in September 2016. The following analyses were conducted for typhoons in August and September from 2001 to 2016 by using the RSMC best track data set and JRA-55 atmospheric reanalysis data set: (a) $k$-means cluster analysis for the typhoon tracks, (b) CPS analysis on the typhoon structural evolution, and (c) composite analysis and case study with regard to the synoptic environments.

On the basis of trial and error, the typhoon tracks were classified into four representative clusters: northeastward (NE), northward (N), westward (W), and northwestward (NW). The results showed that the typhoon tracks were directed in August 2016 more northward than those in August from 2001 to 2015. The results of the CPS analysis indicated that ET in August 2016 had a more indistinct structural change to the cold-core structure with a short duration compared with those from 2001 to 2015.

Furthermore, this study compared the synoptic environments for the typhoons in August 2016 with the composite of the synoptic environments for those in August from 2001 to 2015. The synoptic environments for a specific typhoon in August 2016 were also compared with those in September 2016. The results suggested that both the upper-tropospheric jet stream with enhanced undulations and the mid-tropospheric trough with increased amplitudes located west of Japan merged with the typhoons in August 2016; the typhoons moved northward along the western edge of the high. These characteristics
corresponded well with the results of the cluster analysis. Furthermore, warm moist air was transported toward Japan along the western edge of the high in August 2016. These synoptic environments in August 2016 resulted in the northward typhoon tracks, frequent ET, and indistinct structural change to the cold-core structure.

This study had two major findings:

(1) The typhoons in August 2016 moved northward and underwent ET with an indistinct structural change to the cold-core structure.

(2) The synoptic environments in August 2016 were characterized by the enhanced undulations of the upper-tropospheric jet stream, increased amplitudes of the mid-tropospheric trough, and relatively warm moist air around the typhoon in the lower troposphere.

Furthermore, this study raises the following question: “What brought the unusual synoptic environments in August 2016?” It also raises the imperative to discuss in future studies the synoptic environments that determine the precipitation distributions.

Acknowledgments

We are sincerely grateful to the editor and the two reviewers for their valuable comments that helped improve the manuscript. This study was supported by the Japan Society for the Promotion of Science Grants-in-Aid for Scientific Research (KAKENHI) (Grant No. JP15K05292).
References

Aonashi, K., J. Awaka, M. Hirose, T. Kozu, T. Kubota, G. Liu, S. Shige, S. Kida, S. Seto, N. Takahashi, and Y. N. Takayabu, 2009: GSMaP passive microwave precipitation retrieval algorithm: Algorithm description and validation. *J. Meteor. Soc. Japan*, **87A**, 119–136.

Arnott, J. M., J. L. Evans, and F. Chiaromonte, 2004: Characterization of extratropical transition using cluster analysis. *Mon. Wea. Rev.*, **132**, 2916–2937.

Atallah, E. H., and L. F. Bosart, 2003: The extratropical transition and precipitation distribution of Hurricane Floyd (1999). *Mon. Wea. Rev.*, **131**, 1063–1081.

Atallah, E. H., L. F. Bosart, and A. R. Aiyyer, 2007: Precipitation distribution associated with landfalling tropical cyclones over the eastern United States. *Mon. Wea. Rev.*, **135**, 2185–2206.

Elsner, J. B., and K. B. Liu, 2003: Examining the ENSO-typhoon hypothesis. *Climate Res.*, **25**, 43–54.

Evans, C., K. M. Wood, S. D. Aberson, H. M. Archambault, S. M. Milrad, L. F. Bosart, K. L. Corbosiero, C. A. Davis, J. R. Dias Pinto, J. Doyle, C. Fogarty, T. J. Galarneau, C. M. Grams, K. S. Griffin, J. Gyakum, R. E. Hart, N. Kitabatake, H. S. Lentink, R. McTaggart-Cowan, W. Perrie, J. F. Quinting, C. A. Reynolds, M. Riemer, E. A. Ritchie, Y. Sun, and F. Zhang, 2017: The extratropical transition of tropical cyclones. Part I: Cyclone
Evans, J. L., and R. E. Hart, 2003: Objective indicators of the life cycle evolution of extratropical transition for Atlantic tropical cyclones. *Mon. Wea. Rev.*, **131**, 909–925.

Hart, R. E., 2003: A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon. Wea. Rev.*, **131**, 585–616.

Hart, R. E. and J. L. Evans, 2001: A climatology of the extratropical transition of Atlantic tropical cyclones. *J. Climate*, **14**, 546–564.

Hart, R. E., J. L. Evans, and C. Evans, 2006: Synoptic composites of the extratropical transition life cycle of North Atlantic tropical cyclones: Factors determining post-transition evolution. *Mon. Wea. Rev.*, **134**, 553–578.

JMA, 1990: *Manual of the operational forecasting of tropical cyclones*. Japan Meteorological Agency, 150 pp (in Japanese).

JMA, 2017: *Disaster Weather Report: Natural Phenomenon Report 2017*. No.1, Japan Meteorological Agency, 222 pp (in Japanese).

Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. N. Hanstram, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith, and C. Thorncroft, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting*, **18**, 1052–1092.

Kanada, S., K. Tsuboki, H. Aiki, S. Tsujino, and I. Takayabu, 2017: Future enhancement of
heavy rainfall events associated with a typhoon in the midlatitude regions. SOLA, 13, 246–251.

Kitabatake, N., 2008a: Extratropical transition of tropical cyclones in the western North Pacific: Their frontal evolution. Mon. Wea. Rev., 136, 2066–2090.

Kitabatake, N., 2008b: Extratropical transition of Typhoon Tokage (0423) and associated heavy rainfall on the left side of its track over western Japan. Pap. Meteor. Geophys., 59, 97–114.

Kitabatake, N. 2011: Climatology of extratropical transition of tropical cyclones in the western North Pacific defined by using cyclone phase space. J. Meteor. Soc. Japan, 89, 309–325.

Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical transition of western North Pacific tropical cyclones: An overview and conceptual model of the transformation stage. Wea. Forecasting, 15, 373–395.

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 reanalysis: General specifications and basic characteristics. J. Meteor. Soc. Japan, 93, 5–48.

Kofron, D. E., E. A. Ritchie, and J. S. Tyo, 2010: Determination of a consistent time for the extratropical transition of tropical cyclones. Part II: Potential vorticity metrics. Mon. Wea. Rev., 138, 4344–4361.
Kubota, T., S. Shige, H. Hashizume, K. Aonashi, N. Takahashi, S. Seto, M. Hirose, Y. N. Takayabu, T. Ushio, K. Nakagawa, K. Iwanami, M. Kachi, and K. Okamoto, 2007: Global precipitation map using satellite-borne microwave radiometers by the GSMaP project: Production and validation. *IEEE Trans. Geosci. Remote Sens.*, **45**, 2259-2275.

MacQueen, J. 1967: Some methods for classification and analysis of multivariate observations. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*. University of California Press, Berkeley, 281–297.

Muramatsu, T. 1982: Extratropical transformation of mature typhoon –The case study of typhoon 7916, OWEN. *Tenki*, **29**, 1199–1212 (in Japanese).

Okamoto, K., T. Iguchi, N. Takahashi, K. Iwanami, and T. Ushio, 2005: The global satellite mapping of precipitation (GSMaP) project. *25th IGARSS Proc.*, 3414–3416.

Shimazu, Y., 1998: Classification of precipitation systems in mature and early weakening stages of typhoons around Japan. *J. Meteor. Soc. Japan*, **76**, 437–445.

Sinclair, M. R., 2002: Extratropical transition of southwest Pacific tropical cyclones. Part I: Climatology and mean structure changes. *Mon. Wea. Rev.*, **130**, 590–609.

Thorncroft, C. D., and S. C. Jones, 2000: The extratropical transitions of Hurricanes Felix and Iris in 1995. *Mon. Wea. Rev.*, **128**, 947–971.

Ushio, T., K. Sasashige, T. Kubota, S. Shige, K. Okamoto, K. Aonashi, T. Inoue, N. Takahashi, T. Iguchi, M. Kachi, R. Oki, T. Morimoto, and Z.-I. Kawasaki, 2009: A Kalman
filter approach to the Global Satellite Mapping of Precipitation (GSMaP) from combined passive microwave and infrared radiometric data. *J. Meteor. Soc. Japan*, 87A, 137–151.

Zhong, L. H., S. D. Feng, and L. J. Hua, 2009: A climatology of extratropical transition of tropical cyclones in the western North Pacific. *J. Trop. Meteor.*, 15, 130–147.

List of Figures

Fig. 1. Tracks and positions at TE of all typhoons that underwent (solid lines) and did not (non-ET; broken lines) undergo ET in (a) August and (b) September. The red and blue lines indicate tracks in 2016 and those from 2001 to 2015, respectively. The circles and triangles indicate the positions at TE in 2016 and the positions from 2001 to 2015, respectively.

Fig. 2. Annual number of ET (red bars) and non-ET (blue bar) (typhoons) cases and the ratio of the number of ET cases to that of typhoons in (a) August and (b) September.

Fig. 3. Tracks of typhoons in August and September in the (a) cluster1 (NE), (b) cluster2 (N), (c) cluster3 (W), and (d) cluster4 (NW). The solid and broken lines show the ET and non-ET cases, respectively. The red and blue lines show the tracks in 2016 and those from 2001 to 2015, respectively.
Fig. 4. Movement speed of typhoons for the ET cases (a) before TB and (b) after TE. The vertical and horizontal axes show the north–south and east–west components (km/h), respectively. The closed and open circles show the cases in 2016 and from 2001 to 2015, respectively.

Fig. 5. CPS diagrams in (a) August 2016, (b) August from 2001 to 2015, (c) September 2016, and (d) September from 2001 to 2015. The brown and gray lines indicate the trajectories for the ET cases. The red and black circles indicate the mean trajectories between 72 hours before TE (TE-72h) and 72 hours after TE (TE+72h), respectively. The letters “A” and “Z” indicate TE-72h (or the beginning of the life cycle within the available analyses) and TE+72h (or the end), respectively.

Fig. 6. Time series of the mean parameters of CPS and the mean central pressure (hPa) between 72 hours before TE (TE-72h) and 72 hours after TE (TE+72h) in (a) August 2016, (b) August from 2001 to 2015, (c) September 2016, and (d) September from 2001 to 2015. The blue, red, and green lines show $B$, $-V_f^2$ (left vertical axis), and central pressure (right vertical axis), respectively. The error bars represent the standard deviations.

Fig. 7. 500 hPa geopotential height (contours at the interval of 20 m) in August. Horizontal
distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).

Fig. 8. 300 hPa geopotential height (contours at the interval of 50 m) and wind (colors) in August. Horizontal distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree). The letter “H” indicates a relatively high area (the center of the anticyclonic circulation), whereas the letter “L” indicates a relatively low area (the center of the cyclonic circulation) in the upper panels.

Fig. 9. 850 hPa temperature (contours at the interval of 2 K and colors) in August. Horizontal distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).

Fig. 10. Distributions of the monthly accumulated precipitation (mm) calculated on the basis of the hourly GSMaP dataset in (a) August 2016 and (b) September 2016.
Fig. 11. 300 hPa composite maps in August 2016 for a geopotential height (a, b; contours at the interval of 50 m) and wind (colors) and 500 hPa geopotential height (c, d; contours at the interval of 20 m) at TE-6h (a, c) and TE (b, d). The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).

Fig. 12. Diagram of the characteristics of typhoon tracks and synoptic environments in August 2016. The red lines and purple squares indicate the typhoon tracks and the position of typhoon at TE, respectively. In August 2016, there were enhanced undulations of the upper-tropospheric (300 hPa) jet stream and increased amplitudes of the mid-tropospheric (500 hPa) negatively tilted trough. Moreover, the relatively warm air existed around the typhoon in the lower troposphere (850 hPa). These synoptic environments resulted in the northward typhoon tracks, frequent ET, and indistinct structural change to the cold-core structure.

Fig. 13. Horizontal distributions of the monthly mean (contours) in August 2016 with their anomalies deviated from the monthly mean from 1981 to 2010 (colors) for the 500 hPa geopotential height (a; contours at the interval of 50 m) and 850 hPa temperature (b; contours at the interval of 2 K).
Table 1. Mean positions (latitude and longitude) of a typhoon center at Max, TB, and TE in August and September 2016 and from 2001 to 2015, respectively.
Fig. 1. Tracks and positions at TE of all typhoons that underwent (solid lines) and did not (non-ET; broken lines) undergo ET in (a) August and (b) September. The red and blue lines indicate tracks in 2016 and those from 2001 to 2015, respectively. The circles and triangles indicate the positions at TE in 2016 and the positions from 2001 to 2015, respectively.

Fig. 1. Tracks and positions at TE of all typhoons that underwent (solid lines) and did not (non-ET; broken lines) undergo ET in (a) August and (b) September. The red and blue lines indicate tracks in 2016 and those from 2001 to 2015, respectively. The circles and triangles indicate the positions at TE in 2016 and the positions from 2001 to 2015, respectively.
Fig. 2. Annual number of ET (red bars) and non-ET (blue bar) (typhoons) cases and the ratio of the number of ET cases to that of typhoons in (a) August and (b) September.
Fig. 3. Tracks of typhoons in August and September in the (a) cluster1 (NE), (b) cluster2 (N), (c) cluster3 (W), and (d) cluster4 (NW). The solid and broken lines show the ET and non-ET cases, respectively. The red and blue lines show the tracks in 2016 and those from 2001 to 2015, respectively.
Fig. 4. Movement speed of typhoons for the ET cases (a) before TB and (b) after TE. The vertical and horizontal axes show the north–south and east–west components (km/h), respectively. The closed and open circles show the cases in 2016 and from 2001 to 2015, respectively.
Fig. 5. CPS diagrams in (a) August 2016, (b) August from 2001 to 2015, (c) September 2016, and (d) September from 2001 to 2015. The brown and gray lines indicate the trajectories for the ET cases. The red and black circles indicate the mean trajectories between 72 hours before TE (TE-72h) and 72 hours after TE (TE+72h), respectively. The letters “A” and “Z” indicate TE-72h (or the beginning of the life cycle within the available analyses) and TE+72h (or the end), respectively.
Fig. 6. Time series of the mean parameters of CPS and the mean central pressure (hPa) between 72 hours before TE (TE-72h) and 72 hours after TE (TE+72h) in (a) August 2016, (b) August from 2001 to 2015, (c) September 2016, and (d) September from 2001 to 2015. The blue, red, and green lines show B, $-V_L^T$ (left vertical axis), and central pressure (right vertical axis), respectively. The error bars represent the standard deviations.
Fig. 7. 500 hPa geopotential height (contours at the interval of 20 m) in August. Horizontal distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).
Fig. 8. 300 hPa geopotential height (contours at the interval of 50 m) and wind (colors) in August. Horizontal distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree). The letter “H” indicates a relatively high area (the center of the anticyclonic circulation), whereas the letter “L” indicates a relatively low area (the center of the cyclonic circulation) in the upper panels.
Fig. 9. 850 hPa temperature (contours at the interval of 2 K and colors) in August. Horizontal distributions at (a) TB and (b) TE in T1607 and composite maps at (c) TE-6h and (d) TE from 2001 to 2015. The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).
Fig. 10. Distributions of the monthly accumulated precipitation (mm) calculated on the basis of the hourly GSMaP dataset in (a) August 2016 and (b) September 2016.
Fig. 11. 300 hPa composite maps in August 2016 for a geopotential height (a, b; contours at the interval of 50 m) and wind (colors) and 500 hPa geopotential height (c, d; contours at the interval of 20 m) at TE-6h (a, c) and TE (b, d). The domain centers of the typhoon center are indicated by a blue circle, and the vertical and horizontal axes indicate the distance from the typhoon center (degree).
In August 2016, there were enhanced undulations of the upper-tropospheric (300 hPa) jet stream and increased amplitudes of the mid-tropospheric (500 hPa) negatively-tilted trough. Moreover, the relatively warm air existed around the typhoon in the lower troposphere (850 hPa). These synoptic environments resulted in the northward typhoon tracks, frequent ET, and indistinct structural change to the cold-core structure.
Fig. 13. Horizontal distributions of the monthly mean (contours) in August 2016 with their anomalies deviated from the monthly mean from 1981 to 2010 (colors) for the 500 hPa geopotential height (a; contours at the interval of 50 m) and 850 hPa temperature (b; contours at the interval of 2 K).
Table 1. Mean positions (latitude and longitude) of a typhoon center at Max, TB, and TE in August and September 2016 and from 2001 to 2015, respectively.

| month       | time year | Max lat., lon. [degree] | TB lat., lon. [degree] | TE lat., lon. [degree] |
|-------------|-----------|-------------------------|------------------------|------------------------|
| August      | 2016      | 26.8, 140.9             | 37.3, 140.7            | 38.6, 141.3            |
|             | 2001-15   | 24.4, 134.8             | 32.2, 133.7            | 35.8, 135.9            |
| September   | 2016      | 20.6, 119.6             | 23.8, 115.3            | 27.5, 120.0            |
|             | 2001-15   | 23.5, 138.3             | 32.1, 134.8            | 35.9, 137.5            |