A Role of Environmental Shear on the Organization Mode of Quasi-Stationary Convective Clusters during the Warm Season in Japan

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Abstract

A role of environmental shear on the organization mode of warm-season quasi-stationary convective clusters (QSCCs) was statistically investigated by using operational weather radar and radiosonde data from May to October during 2005−2012. With the use of an ellipse-fitting method, the total number of QSCCs whose shape was determined was 2549. It was found that 87% of the QSCCs have an aspect ratio of larger than 1.4, suggesting that the elongated mode is dominant during the warm season in Japan. The elongated QSCCs were mostly oriented southwest–northeast. The analyses of the environmental shear direction with respect to the orientation of the elongated QSCCs showed that the wind shear direction at the lower troposphere is mainly parallel to the orientation of the elongated QSCCs. A comparison between the elongated and the circular QSCCs with the environmental parameters showed that the lower convective instability and stronger intensity of the low-level shear clearly characterize the elongated QSCC environments. A parameter combining convective instability and shear, bulk Richardson number, characterizes the environmental conditions for determining the organization mode of the QSCCs, suggesting that a back-building mechanism should play a role in generating the elongated QSCCs.

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1. Introduction

The organization of convective systems takes the form of linear, circular, elliptic shapes depending on the vertical profile of horizontal wind speeds. Low- and/or middle-level environmental shears play important roles in controlling convective organization mode over tropical, sub-tropical (Barnes and Sieckman 1984; Alexander and Young 1992; LeMone et al. 1998; Johnson et al. 2005; Cetrone and Houze 2006), and midlatitude regions (Bluestein and Jain 1985; Blanchard 1990; Houze et al. 1990; Rotunno et al. 1988; Parker and Johnson 2000; Seko 2001; Weisman and Rotunno 2004; Schumacher and Johnson 2005; Kato 2005; Takemi 2006, 2007; Seko 2010). Because the vertical shears vary under background synoptic conditions, the mode of convective organization is considered to be modulated by the regional features of the synoptic conditions.

In Japan, most of rainfall systems that spawn heavy rainfall tend to have an elongated structure (see reviews in Ogura 1991; Yoshizaki and Kato 2007). Kato (2005) examined the frequency distributions of the precipitation and found that the elongated convective systems tend to occur when the wind direction at 925−850 hPa levels is southwest. A similar analysis except for the wind direction at the 850-hPa level was conducted by Unuma and Murata (2012). These studies suggest that the low-level shear is one of the important factors to organize the elongated convective systems over the southwestern part of the Japanese islands. The geographical distributions of the elongated convective systems and the circular-shaped convective systems in Japan were examined by Tsuguti and Kato (2014). Although they found the differences in the regional distributions between the two systems, they did not give the reason why the distributions varied depending on the convective modes.

Recently, Unuma and Takemi (2016, hereafter UT16) have examined the environmental conditions for the development of slower-moving or quasi-stationary convective systems during the warm season in Japan and found that there is a correlation between precipitation area and environmental shear. In other words, it was suggested in UT16 that the spatial scale of convective systems is controlled by the shear intensity. However, statistical analyses on convective modes over Japan have not been conducted. In this study, we extend the study of UT16 to investigate the organization mode of quasi-stationary convective clusters (QSCCs).

For the tropical convective systems, the orientation of the faster-moving convective systems is normal to the vertical wind shear, whereas that of the slower-moving ones is parallel to the vertical wind shear (Barnes and Sieckman 1984). Alexander and Young (1992) showed that the shear in the 1000−800 hPa layer, when this is strong, is normal to the convective systems, and that the middle level shear is parallel to the convective systems when 1000−800 hPa shear is weaker. LeMone et al. (1998) summarized the relationship between the orientation of squall lines and the low/middle-level shear. Based on these previous studies, we examine the relationships between the orientation of QSCCs and the environmental shears. Note that the environmental shear is defined as the differential vector of the wind at an upper level minus the wind at a lower level.

The purpose of this study is to investigate the role of environmental conditions on the organized structure of QSCCs by using the numerous samples of the QSCCs extracted by UT16. By objectively identifying and classifying the shape of QSCCs, we statistically investigate the relationship between the shape of QSCCs and environmental parameters. In conducting the statistical analysis, we focus on convective instability and shear conditions, which are controlling factors in determining the organization mode of convective systems (e.g., Weisman and Klemp 1982).

2. Data and method

The total number of QSCC samples examined in this study is 4133 (UT16). In order to identify the shape of QSCCs, we follow the idea of Maddox (1980) who used ellipticity of mesoscale convective systems (MCSs) in determining the morphology of MCSs. For this purpose, we fit the shape of QSCCs as an ellipse and distinguish the shape between circular and elongated systems. To estimate the shape of the QSCCs, an ellipse-fitting method proposed by Fitzgibbon et al. (1999) is used (see Supplement 1). Fitzgibbon et al. proposed a method to determine a two-dimensional elliptical shape by using sequence of points fitted to an ellipse on a two-dimensional plane. UT16 identified the shapes of the QSCCs from operational radar data by setting the minimum threshold of 10 mm h^{-1} of precipitation intensity at the 2 km height above the ground. Using this dataset of the QSCCs, we determine the boundary points of the QSCCs and produce the sequence of points for the QSCCs. With this procedure, we are able to define the shape of QSCCs. We convert the coordinate system from an original longitude-latitude coordinate to a Cartesian coordinate at

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each time of the estimations in order to reduce an error associated with map projection.

After fitting the shape of a QSCC to an ellipse, the center point, orientation, and length of major- and minor-axis of the ellipse-fitted QSCC are obtained. The aspect ratio is defined as the ratio of the length of major- and minor-axis; the orientation of the major axis is represented in the same way as wind direction (i.e., 0 degree means that the orientation is north). The samples which are successfully fitted to the elliptical shapes are statistically analyzed. A possible limitation of this method is to estimate complex shapes of the QSCCs. We applied the method at the time whose area of a QSCC is the largest during the lifetime because the shapes of convective system vary with its lifetime (Maddox 1980; Yang et al. 2015). In addition, a QSCC at its largest size is considered to be highly affected by environmental winds.

In order to identify the dependence of the organization mode of QSCCs on the environmental conditions, environmental stability and shear are examined. The environmental parameters used in this study are similar to UT16; convective available potential energy (CAPE), convective inhibition (CIN), precipitable water (PW), K Index (KI), temperature lapse rate from 850 to 500 hPa (TLR), 0−3 km mean shear (MS03), and 0−3 km environmental helicity (EH03). The upper-air observation data by radiosondes are used to compute the environmental parameters.

3. Results

The number of samples which are successfully determined by the ellipse-fitting method is 2549 among the total number of the QSCCs. Figure 1 shows the frequency distribution of the aspect ratios obtained from the lengths of major- and minor-axis of the identified ellipses. Here, we defined the elongated mode as the aspect ratio is equal to or greater than 1.4 in accordance with the studies by Maddox (1980) and Yang et al. (2015). Eighty-seven percent of the QSCCs is determined as an elongated mode. This result suggests that warm-season QSCCs in Japan tend to have an elongated shape.

The orientation angle of QSCCs in relation to wind shear direction is shown in Fig. 2. Note that we examined only the elongated QSCCs for this analysis. The frequency is the highest when the orientation angle of the QSCCs is 45 degrees. This result indicates that most of the QSCCs are oriented in the southwest–northeast direction.

To see the regional features of the orientation angle of the QSCCs, the distribution of the mode values of QSCC orientations is examined (Fig. 3). In UT16, the frequency of the QSCCs over Japan was counted on a 50 km by 50 km area by accumulating the occurrence of the QSCCs at the original data grid (i.e., 1 km). We evaluate this value on the same areas where the total number of the QSCCs is at least 10. As seen in Fig. 3., the orientation angle between 22.6 and 67.5 degrees (i.e., southwest–northeast) dominates throughout the Japanese islands. Another feature is that the west–east orientation is found in the inland areas of central Japan and in the Tohoku region (i.e., the northern part of the main island of Japan). This distribution of the orientation features seems to be consistent with the previous studies; the southwest–northeast rainbands over the western part of Kyushu Island (Kato 2005) and over Shikoku Island (Unuma and Murata 2012).

Figure 4 shows the relationships between orientations of the QSCCs and environmental shear directions. It is seen in Fig. 4 that overall the orientation of the QSCCs ranges between 0 and 90 degrees, and that the direction of wind shear is in the range of 180 and 270 degrees. Higher frequencies exceeding 8 counts seem to be clustering in these ranges. Among the shears in the different layers shown in Fig. 4, the direction of some shears appears to be linearly correlated with the orientation of the QSCCs, notably in the case of the 1000−700 hPa shear. We also confirmed that the similar characteristics were found for the 925 hPa-based shears.

Previous studies (e.g., LeMone et al. 1998) found that there are convective lines that align in the direction parallel to vertical shears. Based on the idea of the relationship between orientation of convective lines and vertical shears, we calculate correlation coefficients against the line $y = x + 180°$, where x is the orientation angle of the QSCCs, and y is the wind shear direction. The angle 180° here indicates that the orientation of the QSCCs is parallel to the shear direction. Among the shear levels examined here, the highest correlation coefficient (0.590) found for the shear layer of 1000−500 hPa. The second highest value is 0.567 for the 1000−700 hPa shear layer. The values of the correlation coefficients for the cases of 1000−300 hPa, 1000−850 hPa and 1000−925 hPa (0.520, 0.529, and 0.497) are smaller than the other shear layers, respectively. Although the highest value of correlation coefficient

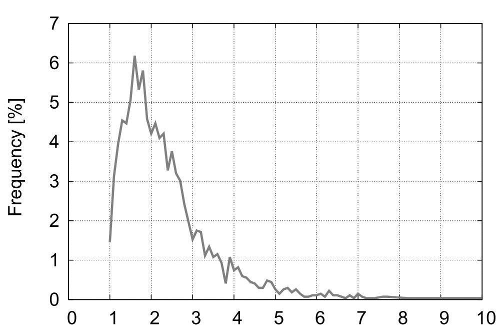

Fig. 1. The frequency distribution of the aspect ratios of the QSCCs. The frequency interval is 0.1.

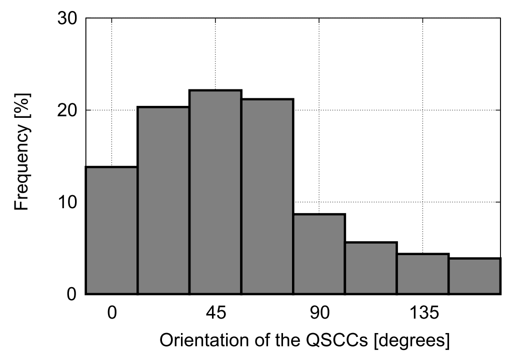

Fig. 2. The frequency distribution of the orientation of the QSCCs estimated by an ellipse-fitting method. The frequency interval is 22.5 degrees. The values show the frequency that is accumulated within the interval as the center of the interval. The orientation is converted to wind direction.

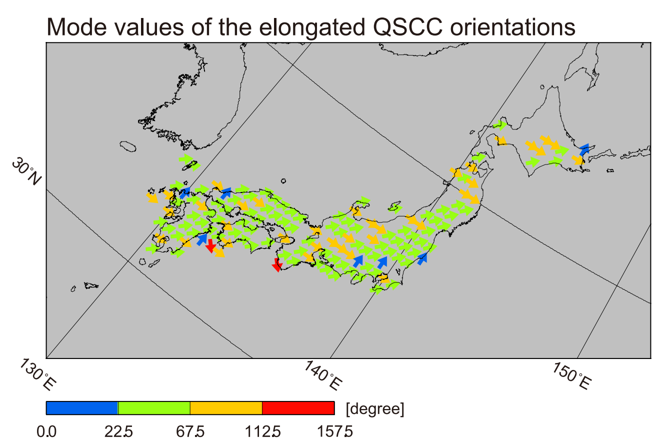

Fig. 3. The distribution of the mode values of the orientation angle for the elongated QSCCs, which are evaluated over the (50-km)^2 area. Note that the values from 0.0 to 22.5 degrees includes the values from 112.6 to 179.9 degrees.

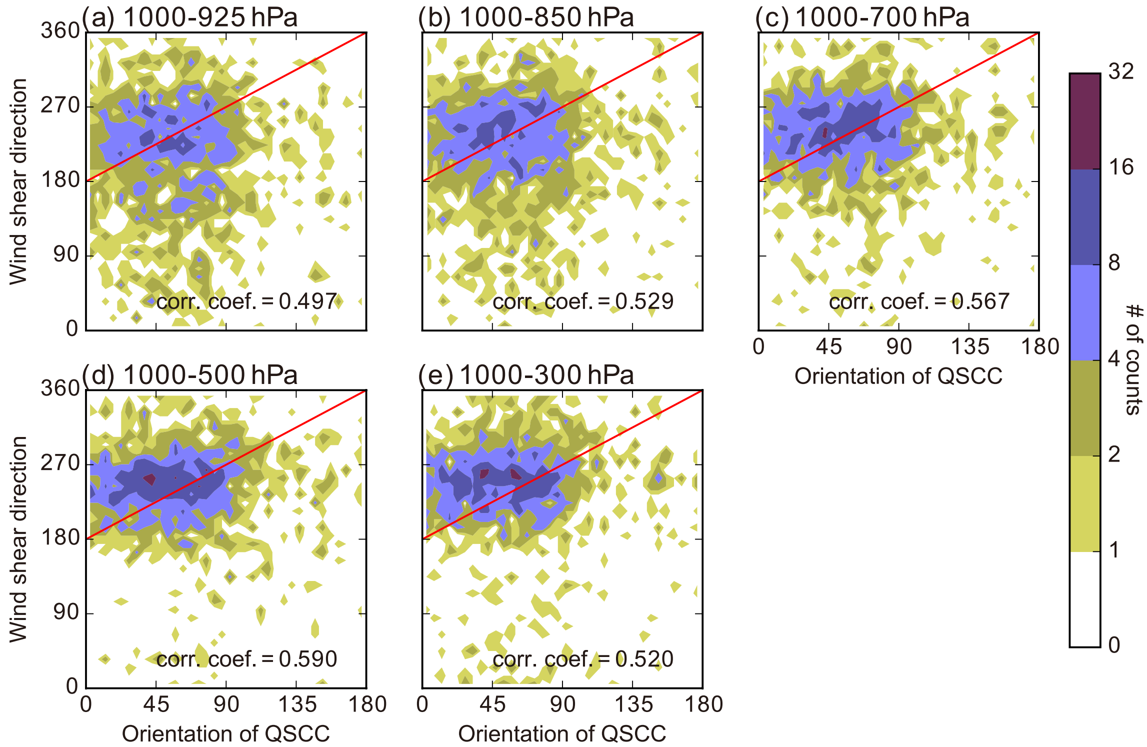

Fig. 4. The relationship of the orientation of the QSCCs at their mature time with the wind direction at the levels of (a) 1000−925 hPa, (b) 1000−850 hPa, (c) 1000−700 hPa, (d) 1000−500 hPa, and (e) 1000−300 hPa, respectively. The frequency is evaluated over the unit mesh of 18 degrees (horizontal axis) × 36 degrees (vertical axis) on the diagram. The red line represented as $y = x + 180°$ (i.e. shear parallel to the major axis of the elongated QSCCs) is also shown for reference. Additionally, correlation coefficients between the distribution and the line are given at the lower-right corner in each panel.

is shown in the 1000−500 hPa-layer, the distribution of the higher frequency value seems to be apart from the line $y = x + 180°$ (Fig. 4d)[1]. Therefore, it is suggested that the elongated QSCCs are mostly parallel to the 1000−700 hPa shear.

Next, we examine the regional characteristics of the QSCC occurrence depending on the different organization modes: the elongated and the circular systems. Figure 5 indicates the frequency of the elongated QSCCs over Japan in terms of the ratio of the elongated QSCC occurrence to the total occurrence of the QSCCs in the area of 50 km by 50 km as well as Fig. 3. In general, the elongated QSCCs occur all over Japan. All the locations indicate 60% or higher occurrence of the elongated systems. The points whose values exceed 95% are distributed near the coastline over the western part of Kyushu Island, Shikoku Island, the Chugoku area, the southern part of Chubu, the Kanto area and Hokkaido. There are some points which have values lower than 80% mostly in the inland regions. This means that the circular QSCCs tend to occur over the inland regions. These results are similar to the study of Tsuguti and Kato (2014); we are able to demonstrate robust features on the difference in the distribution of convective organization mode by using the numerous samples of the QSCCs.

The differences on the convective mode between the elongated and the circular QSCCs are further investigated through the comparison of the environmental conditions of those systems. For this purpose, we examine the environmental parameters as in UT16. The mean values of MS03 and EH03 (CAPE) for the elongated systems are significantly larger (smaller) than those for the circular ones. Other parameters except CAPE, MS03, and EH03 indicate that there is no statistical significance in the differences between the mean values of the elongated and the circular systems. These results suggest that the development of the elongated QSCCs should be diagnosed by a combination of CAPE and

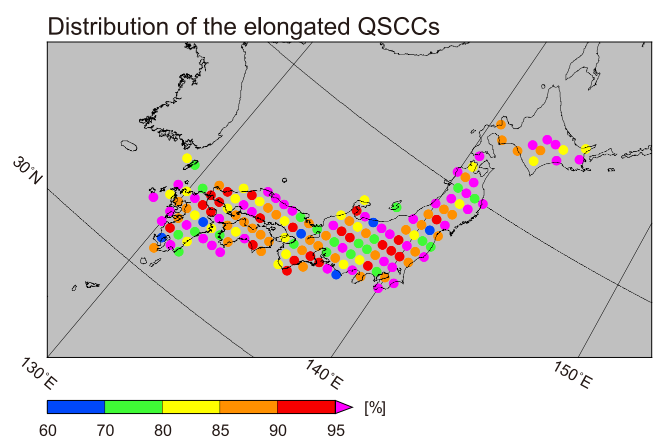

Fig. 5. The frequency distribution of the percentage of the number of the elongated QSCCs to the total number of the QSCCs, which are evaluated over the $(50\text{-km})^2$ area.

shear.

Weisman and Klemp (1982) demonstrated that the storm structure is described with the use of bulk Richardson number (BRN). Based on their study, we investigated the difference of BRN between the elongated and the circular systems. The mean values of BRN for the elongated and the circular QSCCs are 33 and 48, respectively, indicating that the values are within the multicell storm category according to Weisman and Klemp (1982). It was also found that the difference of the values between the two systems is statistically significant. Therefore, it is suggested that the value of BRN significantly distinguishes the environmental properties of the elongated and the circular systems. From this analysis of BRN and the analysis shown in Table 1, stronger vertical shears should play a role in organizing convective clusters into

[1] There is a limitation in conducting the statistical analysis in order to give physical or meteorological meanings.

Table 1. The mean, standard deviation, and *T*-value of the environmental parameters for the elongated (E) and the circular QSCCs (C). Parameters with an asterisk (*) indicate that the mean values between E and C are significantly different at the 95% confidence level. Bulk Richardson number (BRN) is computed by the use of MS03 (i.e. BRN = CAPE/(0.5 ∗ (MS03) ∗ 6000)).

Parameters	Unit	Average (Standard deviation)		T-value
		E	C	(E−C)
CAPE	[J kg^{-1}]	1104 (972)	1321 (987)	−3.53*
CIN	[J kg^{-1}]	18.3 (36.7)	19.5 (40.0)	−0.476
PW	[mm]	48.2 (10.9)	48.6 (10.2)	−0.602
KI	[C°]	29.6 (8.18)	29.7 (7.65)	−0.311
TLR	[K km^{-1}]	5.35 (0.494)	5.38 (0.493)	−0.922
MS03	[$\times 10^{-4}$ s^{-1}]	27.5 (16.5)	22.9 (14.3)	4.97*
EH03	[m^{-2} s^{-2}]	43.8 (103)	26.7 (68.5)	3.64*
BRN	[−]	32.8 (176)	47.8 (271)	−15.9*

a linear shape.

The present results on the relationship between the organization mode of the QSCCs and the environmental conditions are compared with those found in other regions. The CAPE values for the elongated QSCCs are similar to those for the tropical squall lines (Barnes and Sieckman 1984). The slow-moving systems in Barnes and Sieckman (1984) can be regarded as the counterpart of the QSCCs in our study because we focus on quasi-stationary systems. The shear intensity in the direction of the slow-moving convective lines is about 1.5×10^{-3} s^{-1}, which is smaller than MS03 in this study (see Table 1). As Takemi (2006, 2007, 2014) examined the effects of shear on the simulated squall lines, the difference between the QSCCs and the slow-moving lines is probably due to the difference in the shear conditions between the midlatitude and the tropics. It is suggested that the stronger shear in the lower troposphere favors to develop more organized convective systems when the thermodynamic condition (i.e., CAPE) remains the same. Compared to the environmental conditions of squall lines in Oklahoma, the U.S. (Bluestein and Jain 1985), BRN for the elongated QSCCs is equivalent to that for the back-building type. It is noted that the values of CAPE and shear for the back-building squall lines are twice as those for the elongated QSCCs. Among the four types of the squall lines examined in Bluestein and Jain (1985), the back-building type has the strongest shear. In other words, the intensity of vertical shear characterizes the environmental condition of the back-building-type systems. This point as well as the similarity of BRN between the back-building squall lines in Oklahoma and the present QSCCs infers that a back-building process under stronger shear should play a role as a generation mechanism for the elongated QSCCs. It is further suggested that in spite of the difference in thermodynamic and/or kinetic conditions, a combined parameters such as BRN can be used to diagnose the morphology of warm-season QSCCs in Japan or other convective systems in other climate regions.

4. Summary

The relationship between the organization mode of quasi-stationary convective clusters (QSCCs) during the warm season in Japan and the environmental conditions were statistically investigated with the use of operational weather radar and radiosonde data from May to October during 2005−2012.

Using the ellipse-fitting method, we have successfully determined an elliptical shape for 2549 QSCCs. It was found that 87% of the QSCCs have an aspect ratio of greater than 1.4, suggesting that the elongated mode is dominant during the warm season in Japan. The elongated QSCCs are mostly oriented in the direction of southwest–northeast. The regional features of the elongated QSCC orientation were also described. The analyses of the environmental shear direction with respect to the orientation of the elongated QSCCs showed that the shear direction (1000−700 hPa) corresponds well with the orientation of the elongated QSCCs.

The elongated QSCCs were distributed throughout Japan. On the other hand, the circular QSCCs were mainly located in the inland regions. A comparison between the elongated and the circular QSCCs in terms of the environmental parameters indicated that the lower convective instability and the stronger intensity of the low-level shear clearly distinguish the environmental conditions for the elongated QSCCs. A parameter combining convective instability and shear, bulk Richardson number, characterizes the environmental conditions for determining the organization mode of the QSCCs: a lower value of bulk Richardson number is favorable for the elongated QSCCs. The environmental condition for the elongated QSCCs has a similarity with that for the back-building squall lines in the U.S. (Bluestein and Jain 1985). This result suggests that a back-building mechanism under stronger shear should play a role in generating the elongated QSCCs.

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Supplement

Supplement 1 describes the procedure and examples of the ellipse-fitting method proposed by Fitzgibbon et al. (1999).

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