Characteristics and environmental conditions of quasi-stationary convective clusters during the warm season in Japan

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The characteristics and environmental properties of warm-season quasi-stationary convective clusters (QSCCs) in Japan were statistically investigated using operational weather radar and upper-air sounding data from May to October during 2005–2012. The characteristics of the environmental conditions for the development of QSCCs were described through a comparison with those for no-rain cases. We identified 4133 QSCCs over the Japanese major islands. By compiling numerous QSCC samples, the horizontal scales of QSCCs with a circular shape are about 20 km on average with a maximum of 72 km, indicating that warm-season QSCCs in Japan are meso-β-scale phenomena. The analyses of the environmental conditions for the QSCC and no-rain cases showed that the amount of moisture in the lower layer controls the stability condition for the development of the QSCCs, and that the magnitudes of the wind shear and the helicity in the lower troposphere distinguish the kinematic environments for the development of the QSCCs. An increase in the middle-level moisture leads to a larger amount of precipitable water vapour in the QSCC environments, suggesting that atmospheric moistening before the development stage of convection plays an important role in the development of the QSCCs. Additionally, the precipitation intensity has a higher correlation with the convective instability, whereas the precipitation area correlates with the shear intensity. A comparison between slower- and faster-moving CCs indicated that the precipitation intensity of the slower-moving CCs is stronger. This feature is related to a higher convective instability for the slower-moving ones.

Key Words: quasi-stationary convective cluster; moisture contribution; stability; radar analysis; complex topography

1. Introduction

Understanding and predicting warm-season convective rainfall remain challenging tasks from both research and operational perspectives. Warm-season convective rainfall can sometimes be a significant event that spawns water-related disasters. Simply stated, heavier rainfall occurs where a high rainfall rate continues for an extended time (Chappell, 1986; Doswell et al., 1996). As a cause of disaster-spawning heavy rain events, mesoscale convective systems (MCSs) act as key players among weather phenomena during the warm season. MCSs are defined as cloud systems that produce a contiguous precipitation area on the order of 100 km or more on a horizontal scale in at least one direction (Glickman, 2000).

MCSs are widespread phenomena that develop in various climate regions ranging from tropical through subtropical to extratropical regions. It is anticipated that locations with a stronger rainfall rate over an extended period will produce a heavier rainfall in the presence of a longer-lived MCS. From the Eulerian perspective, heavier rainfall is caused by the presence of a longer-lived and stationary (or slow-moving) MCS.

MCSs appear to be quasi-stationary due to two factors: (i) convective cells are continuously generated in similar locations by a back-building process (Bluestein and Jain, 1985) under a stationary or slowly changing synoptic-weather condition (such as a stationary front), and (ii) convective cells are continuously generated by topographic forcing. For example, Schumacher and Johnson (2008) examined an extreme rain event in the United States that occurred under quasi-stationary, synoptic-scale weather conditions where convective cells were successively generated by quasi-stationary forcings. On the other hand, complex topography plays a role in triggering and enhancing flash-flood-producing events over the Alpine region (e.g. Buzzi and Foschini, 2000; Anquetin et al., 2003; Davolio et al., 2009; Panzieri et al., 2014). In addition, quasi-stationary convective systems found in the southern part of the United Kingdom develop due to forcing from sea breezes (Warren et al., 2014).

Quasi-stationary convective systems (QSCSs) are a well-known cause of heavy rainfall in Japan. Such events frequently appear during the warm season (Ogura, 1991; Yoshizaki and Kato, 2007) under the presence of extratropical cyclones, synoptic-scale fronts, tropical cyclones, or stationary fronts such as Baiu fronts. The
The horizontal scale of a precipitating system over Japan is typically on the order of 10 km, which corresponds to the meso-β-scale by the definition of Orlanski (1975).

The environmental conditions necessary to develop QSCSs, particularly during the Baiu season, are characterized by a larger moisture content (Kato, 2006; Hirockawa and Kato, 2012). Higher environmental moisture may be a common feature for MCS events over East Asia; for example, Meng et al. (2013) showed that precipitable water is higher for the MCSs in east China than for those in the USA. In addition to such humid conditions, kinematic effects such as low-level convergence and vertical shear of horizontal winds play important roles in maintaining QSCSs (Kato, 1998; Kato and Goda, 2001; Yoshizaki et al., 2000; Kato and Aranami, 2005). Kato (2005) examined the conditions favourable for the development of QSCSs over Kyushu Island, which is located in the western part of Japan, and found that the presence of persistent southwesterly winds is required to form QSCSs. In addition, Yoshizaki et al. (2000) showed that topographic forcing is important to trigger convective clouds and organize QSCSs over the western part of Kyushu Island. In this way, many studies have investigated QSCSs with significant societal impacts and/or have conducted special campaigns on a case-study basis.

However, few have investigated the statistical or climatological features of QSCSs in Japan by compiling numerous samples. One exception was conducted by Chuda and Niino (2005); through an investigation of the features of the background atmospheric conditions over Japan using radiosonde data, they showed that the environmental parameters strongly depend on the location and the season. Convective available potential energy (CAPE) values generally become larger at lower latitudes and during the warmer season; thus, convective storms favour development in the southern parts of Japan during the warmer season. Because their study did not distinguish the environmental conditions for convective events from non-convective events, the environmental characteristics for the development of QSCSs in Japan remain unknown.

The distinction between convective and non-convective environments should help our understanding on the general conditions necessary to develop convective precipitation. A statistical analysis for afternoon thunderstorms over the Kanto area (Figure 1(b)) in the summer was conducted by Nomura and Takemi (2011). Nomura and Takemi examined eleven environmental parameters for afternoon rain cases by comparing with no-rain cases with the use of mesoscale-gridded analysis data from the Japan Meteorological Agency (JMA) as well as the radiosonde data observed at Tateno (Figure 1(b)). The K Index significantly distinguishes the environmental conditions between the rain and the no-rain cases. They also investigated the vertical structures of temperature and moisture, and concluded that lower temperatures at middle levels and higher humidity at low to middle levels are the conditions favourable for afternoon rains.

A similar analysis was conducted for afternoon rain events in and around the Nobi Plain in central Japan (Takemi, 2014a). In addition, Kato (2006)’s case-studies suggested that the middle-level moisture plays an important role in determining the

Figure 1. The locations of (a) the operational radar sites (crosses) and (b) the radiosonde sites (grey dots). In (a), the detecting ranges of the operational radars are shown by solid circles, and the grey shading indicates surface elevation at 500 m intervals. See the text for the acronyms of the radiosonde sites in (b).
development of convective systems. However, statistical studies that specifically focus on QSCCs have yet to be conducted. In this study, which focuses on various types of convective system, including a cluster of convective clouds, we refer to QSCCS as quasi-stationary convective clusters (QSCCS).

The purpose of this study is to reveal the climatological features of QSCCS, including lifetime, location, rain intensity, and the environmental properties for the development of QSCCS during the warm season over Japan. The analyses were performed using operational radar and upper-air observation data. To identify QSCCS, we modified a method to detect an individual convection cell within a precipitating area from radar observations (Shimizu and Uyeda, 2012). The environmental characteristics for the development of QSCCS were examined in terms of the environmental parameters by comparing QSCC events and no-rain cases using an idea similar to Nomura and Takemi (2011) and Takemi (2014a). From the environmental analyses, we revealed the conditions favourable for the development of QSCCS from a climatological point of view. Because Barnes and Sieckman (1984) showed that there are similarities and differences in the environments for fast- and slow-moving mesoscale convective cloud lines over the Tropics, we also examined the differences of the characteristics and environmental properties of QSCCS by dividing them into sub-groups based on their propagation speed (i.e. slower-moving CCs and faster-moving CCs). Through a demonstration of the specific parameters used to diagnose the development of QSCCS, it is emphasized here that statistical information can be useful as a better forecasting guide for the development of QSCCS.

2. Data and methodology

2.1. Data

The data observed during the warm season, i.e. from May to October, during 2005–2012 are used in this study. To identify QSCCS, we use operational radar data from the JMA. In this dataset, the radar reflectivities from 19 elevation angles within the detection range of 200 km are converted to precipitation intensities (mm h\(^{-1}\)) at a height of about 2 km. This study uses this precipitation intensity dataset. The horizontal resolutions on the longitude–latitude grid is approximately 1 km, and the temporal interval is 10 min, which are adequate for identifying and tracking QSCCS all over Japan. Since the present study deals with QSCCS that develop over land, the area for the analysis of the radar precipitation intensity is limited to the Japanese major islands and the surrounding region within 10 km of the coast. The locations and ranges of those radars are shown in Figure 1(a).

The upper-air sounding data by radiosondes are used to examine the environmental conditions for the development of the extracted QSCCS. Figure 1(b) shows the locations of these stations: Wakkanai (WKN), Sapporo (SPR), Kushiro (KSR), Nemuro (NMR), Akita (AKT), Wajima (WJM), Tateino (TTN), Hamamatsu (HMT), Matsue (MTE), Yonago (YN), Shionomisaki (SNM), Fukuoka (FKO), and Kagoshima (KGS). Note that the Nemuro (Yonago) station was re-located to Kushiro (Matsue) in March 2010, and thus these two should be regarded as the same station. We consider that the differences that may arise owing to this re-location are minimal in the analysis because they belong to similar climate regions. The times of the upper-air observations are 0900 and 2100 Japan Standard Time (JST), which is 9 h ahead of UTC. Hereafter the times are referred to as JST.

2.2. Identification and tracking of QSCCS

To extract QSCCS, we use Algorithm for the Identification and Tracking Convective Cells (AITCC) which was developed by Shimizu and Uyeda (2012). This algorithm was originally intended to identify and track individual convective cells within an MCS. We modify the algorithm for identifying and tracking QSCCS. The procedures of how to extract QSCCS are described here.

The first procedure is to extract convective clusters (CCs). At every time step, we define a contiguous area of the precipitation intensity that is equal to or greater than a prescribed threshold from the radar observations (Figure 2(a)). The minimum threshold is set to be 10 mm h\(^{-1}\) from the reflectivity–rainfall intensity relationship used by JMA, in order to extract convective regions. The threshold of 40 dBZ, which was used by Steiner et al. (1995) and Geerts (1998) to identify convective echoes, is modified from the original AITCC algorithm which used the threshold of 30 dBZ (Shimizu and Uyeda, 2012). If the contiguous area is equal to or greater than 200 km\(^2\), the precipitation area is defined as a CC (Figure 2(b)). In most cases, multiple CCs are extracted at every time step. These extracted CCs are labeled with different identification numbers (ID) as shown in Figure 2(b).

The second procedure is to identify quasi-stationary of CCs. Here we track the extracted CCs in time series and identify the lifetime of the QSCCS (Figure 2(c, d)). Figure 2(c) schematically depicts the centroids and defined areas of two CCs: one at time \(t\) and the other at \(t + d\) (\(dt\) is the time difference). From these CCs, an overlapped-area is determined by the areas of the CCs at \(t = T\) and \(t + d\) (Figure 2(d)). At the same time, a motion vector is defined by pointing the centroid of the CC at \(t = T\) and the centroid of the CC at \(t + d\) which was used by Steiner et al. (1995) and Geerts (1998) to identify the motion vector. The magnitude of motion vector and the size of an overlapped area are used to determine the identity of a CC. The threshold of the maximum motion vector and the minimum overlapped area were set to be 16.7 m s\(^{-1}\) and 1 km\(^2\) (corresponding to one grid point in the 1 km horizontal resolution of the radar data), respectively, in the original algorithm of Shimizu and Uyeda (2012). The threshold for the motion vector is changed to 10 m s\(^{-1}\) in the present study. Thus, if the magnitude of the motion vector is equal to or smaller than 10 m s\(^{-1}\), the CC at \(t = T\) and \(t + d\) is regarded as the same system as the CC at \(t = T\). In this way, QSCCS are defined.

When a CC at \(t = T\) has multiple candidates at \(t + d\) in this tracking procedure, a single CC that is the most likely linked to the CC at \(t = T\) is determined with the tracking algorithm of AITCC (details given in section 2.4 of Shimizu and Uyeda, 2012). When a CC at \(t = T\) has no candidate CCs at \(t + d\), the tracking algorithm stops. This time \(t = T\) is defined as the end of the lifetime of a QSCC. Here, the QSCCs whose lifetime is less than 20 min are excluded, because the lifetime should be resolved by at least three time steps of the radar data. A possible limitation of the present method is that the method is not able to track a CC which propagates discretely; if there are no overlapping areas of CCs at \(t = T\) and \(t + d\), the CCs are not classified as the same CC. This limitation may bias the results toward shorter lifetimes.

2.3. Environmental indices and parameters

Environmental conditions before the development of the extracted QSCCS are investigated with the use of upper-air sounding data. For each QSCC, a sounding station which is within the 200 km from and the nearest to the centroid of the QSCC is used. The atmospheric conditions at times within 1–9 h prior to the developments of the extracted QSCCS are defined as the environments before the QSCC occurrence; the sounding data at these times are used for the present analysis. In other words, we do not use data at 0–1 and 10–11 h before the QSCC development, because the data at 0–1 h before may strongly be affected by QSCCs themselves and the data at 10–11 h before may not reflect the environments before the development of QSCCS.

The environmental conditions are diagnosed in terms of indices and parameters related to static stability and vertical wind shear. There are a number of environmental indices and...
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parameters that are related to stability and shear conditions (e.g. Markowski and Richardson, 2010). The parameters examined here are CAPE, convective inhibition (CIN), precipitable water (PW), Showalter Stability Index (SSI), K Index (KI; George, 1960), temperature lapse rate from 850 to 500 hPa (TLR; Takemi, 2007a, 2007b), 0–3 km mean shear (MS03; Rasmussen and Blanchard, 1998), and 0–3 km environmental helicity (EH03; Davies-Jones, 1984). CAPE is calculated by adiabatically raising a parcel whose properties are vertically averaged in the lowest 500 m; in calculating CAPE the effects of condensate loading, entrainment, and latent heat of fusion are neglected, and buoyancy is defined with virtual temperature. In cases when the level of free convection is not identified, the values of CAPE and CIN are not obtained and hence not used for the statistical analyses described later. Choosing the 850 and 500 hPa levels for the TLR calculation is based on an idea of comparing the effects of lapse rate and moisture in the definition of KI. The environmental property of EH03 is used to see how large the hodograph curvature is.

Another important factor for the development of QSCCs is a lifting effect. However, we do not address the lift due to the limitation of the radiosonde observations, since there is difficulty in estimating large-scale lifting from a single sounding.

For the purpose of comparing the environmental conditions before the development of the extracted QSCCs, environmental conditions for no-rain cases are also examined. The no-rain cases are defined as having no radar-observed precipitation at any grid points within the 200 km distance from the radiosonde sites between the observation times. It should be noted that, once a radiosonde observation is associated with a certain QSCC, it is no longer used for other QSCCs or a no-rain case. A single observation is used only once and counted only once for the composite. Statistical significance of the differences of the environmental parameters between the QSCCs and the no-rain cases is also examined.

3. Results

3.1. General characteristics of the extracted QSCCs

In this subsection, we will present overall characteristics of the extracted QSCCs. The total number of the extracted QSCCs is 4133, while the total number of no-rain cases for a comparison purpose is 99 673.

The frequency distribution of the temporal and spatial means of precipitation intensity averaged for all the QSCCs is shown in Figure 3. Note that by definition the minimum value of the mean precipitation intensity is 10 mm h\(^{-1}\) (section 2.2). A peak in the frequency distribution is seen at 20 mm h\(^{-1}\), while the mean, median and maximum values are 22.3, 21.5 and 54.0 mm h\(^{-1}\), respectively.

\footnote{Student’s t-test is used to show the statistical significance in this study. If a distribution shows the one tail, the Mann–Whitney U test will be additionally applied.}

\footnote{This number means the number of the detected events on the radar data. Note that the actual total number for the no-rain environments is reduced to 7619 (details are given in Figure 8 and the related descriptions).}
The frequency at a rain rate \( r \) means the value accumulated over the rain rate between \( r - 2.5 \) and \( r + 2.5 \).

Figure 3. Frequency distribution of the time-mean precipitation intensity averaged for the lifetime of each QSCC, counted at intervals of 5 mm h\(^{-1}\). The frequency at a rain rate \( r \) means the value accumulated over the rain rate between \( r - 2.5 \) and \( r + 2.5 \).

Figure 4 shows the frequency distribution of the temporal mean of precipitating area for all the QSCCs averaged during their lifetimes. By definition the minimum value is 200 km\(^2\). The frequency decreases with the increase in the precipitation area. Because of the shape of the distribution, the mean and median values are different: 329 and 286 km\(^2\), respectively. The number of events with a large precipitation area becomes significantly reduced; the upper limit of the mean precipitation area identified in this analysis is 3961 km\(^2\). If these areas are assumed to have a circular shape, the mean and the maximum equivalent radius is about 10 and 36 km, respectively. Thus, it can be assumed that typical sizes of the QSCCs with a circular shape assumed are about 20 km on average and 72 km at the maximum. The examination of the sizes of the extracted QSCCs at all the time steps indicated that the maximum QSCC area is 10 616 km\(^2\), which is one fifth of a mesoscale convective complex (e.g. Maddox, 1980) of 50 000 km\(^2\). This is a typical cloud area. This maximum area corresponds to the equivalent radius of 58 km, which indicates that the maximum horizontal size of QSCCs is about 120 km. Therefore, it is simply stated that the QSCCs in Japan are meso-\( \beta \)-scale phenomena. The horizontal scale of the QSCCs at their mean is smaller than that of a typical MCS, i.e. meso-\( \alpha \)-scale (Glickman, 2000). This is considered to be related to their shear environments, which will be examined in sections 3.4 and 3.5.

Figure 5. Number of QSCCs versus their lifetimes, counted at 10 min intervals.

The spatial distribution of the occurrence of QSCCs is shown in Figure 6(a). The location of each QSCC is defined as a point at which the QSCC is initially identified during the tracking procedure. A number of events is assessed in a unit area of 50 km \( \times \) 50 km in order to see the general characteristics by filtering out small-scale features. It is seen that QSCCs occur frequently on the Pacific side of the Japanese islands and the western part of Japan. Frequent occurrence is also seen on the Sea of Japan side and the inland regions in central Japan. The frequency is generally lower in northern Japan than in the other regions. By comparing the spatial pattern in Figure 6(a) with terrain features (Figure 1(a)), we can also note that overall the points with frequency greater than or equal to 30 counts correspond well to regions with or near high elevation and/or mountainous topography.

To see how the amount of rainfall induced by QSCCs contributes to the total amount of rainfall during the warm season, the percentage of the total rainfall due to the extracted QSCCs to the total amount of rainfall during the warm season is examined and is shown in Figure 6(b). The percentage is seen to be higher in the western part and the Pacific side of the Japanese islands. In particular, higher values of greater than 3% are found over Kyushu, the southwestern part of Shikoku, the southern part of Kinki, and the north and the northwestern part of Kanto. The spatial distribution of the occurrence of the QSCCs may be associated with a regional feature of the environmental parameters, which will be mentioned in section 3.3.

Based on Figure 6, the whole analysis region of Japan is divided into three regions. The first region is the Hokkaido region, where both the frequency and the rainfall contribution of QSCCs are the lowest. Regions with higher frequency are divided into the Sea of Japan side region, and the Pacific side region. The radiosonde sites in the Hokkaido region are WKN, SPR, KSR, and NMR; those in the Sea of Japan side region are AKT, WJM, YNG, and MTE; and those in the Pacific side region are TTN, HMT, SNM, FKO, and KGS. As a representative of each region, stations SPR, AKT, and KGS are chosen for the Hokkaido, the Sea of Japan side, and the Pacific side regions, respectively (e.g. Chuda and Niino, 2005). By dividing the whole analysis area in this way, the environmental conditions for QSCC development are examined, which will be described in section 3.2.

The temporal change of the QSCC characteristics during the warm season is investigated on a monthly basis. Figure 7 shows the monthly changes in the total numbers of the QSCCs. The number of QSCCs exceeds 500 from July to September, having a peak in August, while numbers in May and October are reduced. The higher frequency of QSCCs is considered to be due to Asian monsoon activity (rainy season) in June and July, and eventual tropical cyclones and stationary fronts from August to September. One thing to be noted here is that the rainbands associated with tropical cyclones are included in the extracted QSCCs in this study, because we investigate various types of convection.
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To show how frequent rainfall events occur during the warm season, we examine the percentage of the number of no-rain cases to the total number of the radiosonde observation times. Figure 8 shows the month-to-month change of this no-rain percentage as well as the actual number of no-rain cases. In contrast to the features found in Figure 7, it is seen from Figure 8 that the percentage and the actual number of the no-rain cases are lower from July to September, while they are the highest in May. Although the features of June and October seem to be similar, the occurrence of QSCCs is lower in October than in June (Figure 7).

Based on the monthly features shown in Figures 7 and 8, the warm season from May to October is categorized into three sub-seasons. May and October are spring and autumn, respectively, and are summarized as the same sub-season, referred to as Season 1 (denoted as S1). June, which belongs to a rainy season because of the higher activity of the Asian monsoon, is defined as Season 2 (hereafter S2). July-August-September is defined as Season 3 (hereafter S3). Based on this categorization, the environmental properties of QSCCs are investigated in the following section.

3.2. Vertical structure of the environmental atmosphere

In this subsection, we examine the vertical structure of the environmental atmosphere for the development of the extracted QSCCs (denoted as Q category) by comparing with those for the no-rain cases (denoted as N category). The vertical profiles at SPR, AKT, and KGS are averaged for each season, i.e. S1, S2, and S3.

Firstly, the characteristics of the vertical profiles of temperature, moisture, and wind are described to provide overall views of the stability and shear conditions that will be given in the next subsection. The vertical profiles of temperature, water vapour mixing ratio, and relative humidity for Q and N are shown in Figure 9. A common feature found in the temperature profiles is that temperatures below 850 hPa and above 400 hPa are higher in Q than in N for all three sites in all the seasons (Figure 9(a, d, g)), which are statistically significant at a confidence level of 95% (Figure 10(a, d, g)). On the other hand, temperatures at the middle levels do not show a consistent feature between Q and N, although they are a little higher in Q than in N. Note that the $T$-values at the 600 and 700 hPa levels are smaller, which suggests that the statistical significance of the difference may be marginal. The smaller $T$-values at the middle levels are also seen in HMT, MTE, and YNG in the season S3 (Figures SI-6(d) and SI-7(d) of File S1).

In contrast to the temperature profiles, the difference of water vapour mixing ratio and relative humidity between the categories is clearly identified. Water vapour mixing ratio and relative humidity throughout the troposphere are higher in Q than in N for all three sites in all the seasons (Figure 9(b, c, f, h, i)). The differences described above are also statistically significant.
at the 95% level (Figure 10(b, c, e, f, h, i)). On the other hand, there is no significant difference in the water vapour mixing ratio between Q and N in the lower and upper troposphere in S2 at SPR (Figure 10(b)). This feature is also seen in WKN in seasons S1 and S2 (Figures SI-1(b)–(c) and SI-5(b)–(c) of File S1). Considering these features, it should be noted that the environments for the development of QSCCs are characterized as both higher temperature in the lower troposphere and higher moisture throughout the troposphere during the warm season in Japan. These differences of temperature and moisture between the categories will affect the diagnosis of stability conditions, which will be described in the next subsection.

The features of the wind profiles can be obtained from the hodographs. Figure 11 compares the mean wind hodographs in Q and N depending on the site and the season. The differences in the shapes of the hodograph between the categories are clearly seen. The shapes in Q indicate a clockwise veering feature from the surface to about 700 hPa and a nearly unidirectional structure above that level. On the other hand, in N, a wind veering is not seen at the lower levels, while slight anticlockwise feature can be identified at the middle-to-upper levels in some sites/seasons. One of the pronounced features on the hodograph curvatures in Q is that easterly winds are seen in the lower troposphere at all three sides in the lower troposphere at all three sites (Figure 11(a)–(c)). This feature is mostly seen over the Pacific side in season S1, which is related to larger hodograph curvature in Q. In addition, the hodograph shapes and the direction of rotation strongly depend on the meridional wind at all the three sites in all the seasons. Most of these differences of zonal and meridional winds between Q and N are statistically significant at the 95% confidence level (Figure 12), except for the zonal wind in seasons S1 and S2 (Figure 12(a, c, e)). The significant difference seen here corresponds to the difference of the hodograph curvature between Q and N. The statistical difference suggests that the clockwise veering in Q and the anticlockwise veering in N control the shear condition for the development of QSCCs.

If the environmental winds are assumed to be geostrophic winds, there is warm advection associated with the clockwise veering feature in Q (in terms of thermal wind balance). In addition, the hodographs in Q are consistent with the environments on the warmer side of warm or stationary fronts, which is a common place for the development of convective systems (Laing and Fritsch, 2000). Here, warm air advection is one of the forcing terms for ascent in the quasi-geostrophic approximated ω-equation, and thus it is suggested that the hodograph shape in Q is related to the large-scale ascent. Although other conditions (e.g. an intrusion of the jet in the upper troposphere) are required to induce large-scale ascent, one possibility for the existence of large-scale ascent is demonstrated from the hodograph.

Based on the analysis of the characteristics of the vertical profiles, the environmental properties for the development of QSCCs will be described in the following subsection with the use of some stability and shear indices that characterize environmental conditions. The comparison between Q and N will also be provided.

3.3. Diagnosis of conditions for the development of QSCCs with environmental parameters

As described in section 2.3, the environmental conditions for the development of QSCCs are diagnosed in terms of stability and shear parameters. A diagnosis with the use of these parameters is useful for identifying the differences in environmental conditions between Q and N.

Figure 13 shows the frequency distributions of the environmental parameters in Q and N. To see general characteristics of the environmental parameters throughout Japan, all the data shown in Figure 13 are composited for all the analysis sites. Except for TLR, the differences of the parameters between Q and N are clearly seen. Compared to N, Q indicates a larger amount of PW, a higher degree of instability (SSI, KI, and CAPE), and stronger shear (MS03) with a larger hodograph curvature (EH03). Considering that there is a large difference of PW while little difference of TLR between the categories, the moisture difference seems to control the differences seen for other stability parameters as indicated by SSI (Eq. (A1)), KI (Eq. (A2)), and CAPE.

From the analyses of vertical profiles of moisture, it was found that the moisture is larger in Q than in N throughout the troposphere. Considering that SSI, KI, and CAPE become larger with a larger amount of moisture content in the lower troposphere and that temperature lapse rate was indicated to be near saturated neutral (moist adiabatic), it is suggested that the amount of moisture in the lower layer controls the stability condition for the QSCCs. The comparison between Q and N will also be provided.

Table 1 summarizes the averages and standard deviations of those environmental parameters. The statistical significance of the differences in the mean values between Q and N is examined with the test statistic T*, which is shown in Table 1 for the environmental parameters. As expected from the features seen in Figure 13, it is found that all the environmental parameters except TLR indicate a significant difference between Q and N. Overall the T*-values substantially exceed the significance level, and the T-values for PW and KI are the highest ones among the parameters. Because KI takes into account the effects of moisture at each vertical level. Therefore, the difference of the water vapour contents between Q and N is considered to control the environmental properties for the development.
of QSCCs rather than the difference of temperature lapse rate. The moisture content at each height will be discussed below. As far as the kinematic parameters are concerned, both MS03 and EH03 indicate that there are significant differences between the categories. Thus, the magnitude and direction of wind shear in the lower troposphere also characterize the difference between Q and N.

The distributions of CAPE, PW, and MS03, whose values are averaged during the warm season at each site, are shown in Figure 14 in order to see the regional features of environmental parameters. CAPE, PW, and MS03 are selected to examine stability, moisture, and shear conditions, respectively. The values of CAPE and PW mostly increase with the decrease in the latitude. The regional feature of CAPE is consistent with the previous findings of Chuda and Niino (2005). In contrast, the values of MS03 are larger in the Hokkaido region and in the southern part of Japan (SNM and KGS) (>13.0 × 10^{-4} \text{s}^{-1}) than in the middle of Japan (TTN, HMT, MTE, YNG, and FKO) (<13.0 × 10^{-4} \text{s}^{-1}). Compared with Figure 6, larger populations of QSCCs are mostly seen at locations with the larger values of CAPE and PW.

The seasonal and regional variations of the environmental parameters are further described here. Because of the significant differences between Q and N, the variations of the environmental conditions for QSCCs are examined by concentrating on PW and KI. Figure 15 shows the variation of the monthly means of PW and KI. Each panel in Figure 15 summarizes the variations for each region. Both PW and KI unanimously indicate higher values in Q than in N at all the locations in all the months. In other words, the significant differences found in the overall averages shown in Table 1 are consistently seen throughout the regions during the warm season. The variations of PW and KI during the

months show that highest values for Q are generally seen in July and August. PW and KI show lowest values in May and October.

The results described above show that the moisture content is the most distinguishing factor in characterizing the environmental conditions for the development of QSCCs from no-rain cases among the stability parameters. Although PW is found to be an important parameter, the levels at which moisture content contributes to PW are not known. Because it was found that middle-level humidity plays an important role in controlling the structure and intensity of cumulus convection and MCSs (Derbyshire et al., 2004; Takemi et al., 2004; Takemi, 2007a, 2014b, 2015), the moisture content at each vertical layer and its contribution to the total amount of moisture (i.e. PW) are examined here. For this purpose, the vertically integrated water vapour contents in vertical layers of 1 km depth are computed. The vertically integrated water vapour contents from the height of X km to Y km are referred to as PWXY; for example, the water vapour content vertically integrated from 0 to 1 km is referred to as PW01.

The differences between Q and N in the layer-integrated moisture content are compared in terms of frequency distribution. The moisture content in all the layers is consistently larger in Q than in N (not shown). In addition, the difference between the categories appears to be more pronounced with the increase in the height level. This result indicates that the environmental conditions for QSCCs are characterized by a larger amount of moisture at middle levels.

The importance of middle-level moisture content can also be found for the difference of the contribution of the layer-integrated moisture to the total amount of moisture, i.e. PW. Thus, we examined the contribution of the layer-integrated moisture content at each layer to the total PW (Figure 16). Compared with the difference of the frequency distributions between Q and N in the lower layers, the departure of the distribution in Q

Figure 10. As Figure 9, but showing the $T$-values of the differences in mean values between QSCCs (Q) and no-rain cases (N). Points marked in red and cyan indicate that the $T$-values are significant at the 95% confidence level.
becomes more distinct from the N distribution with the increase in the layer height. That is, the amount of moisture at middle levels largely contributes to precipitable water vapour in the environments of Q. Considering that PW is significantly larger in Q than in N, it is suggested that an increase in the middle-level moisture leads to a larger amount of PW for the development of the QSCCs.

The environmental condition with a larger amount of mid-level moisture was also identified for convective precipitation events in the afternoon during the summer over the plain regions (the metropolitan areas of Tokyo and Nagoya) facing the Pacific in Japan (Nomura and Takemi, 2011; Takemi, 2014a). The present analysis is consistent with these previous findings. Therefore, a larger amount of moisture is considered to be a common feature that distinguishes the environments for the development not only of summertime thunderstorms but also organized convective systems during the warm season in Japan. One thing to be noted here is that higher middle-level moisture controls the convective development over the Tropics (Takemi et al., 2004; Kikuchi and Takayabu, 2004) and the western part of Kyushu Island (Kato, 2006). At the mature stage of the QSCCs, the moisture at the middle level controls the development associated with the convective systems (Kato, 2006): the wet (dry) environment in the mid-troposphere gives a condition favourable (unfavourable) for the development of convective systems. Considering that higher middle-level moisture controls the development of convection, it is emphasized that atmospheric moistening before the development stage of convection plays an important role in the development of the QSCCs.

3.4. Relationships between environmental conditions and rainfall characteristics

In the previous subsection, the environmental properties for the development of the QSCCs were investigated by comparison with the no-rain cases. Differences in the environmental properties between the QSCC occurrence and the no-rain cases were demonstrated. In this subsection, the dependence of the intensity of Kyushu Island (Kato, 2006). At the mature stage of the QSCCs, the moisture at the middle level controls the development associated with the convective systems (Kato, 2006): the wet (dry) environment in the mid-troposphere gives a condition favourable (unfavourable) for the development of convective systems. Considering that higher middle-level moisture controls the development of convection, it is emphasized that atmospheric moistening before the development stage of convection plays an important role in the development of the QSCCs.

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In the previous subsection, the environmental properties for the development of the QSCCs were investigated by comparison with the no-rain cases. Differences in the environmental properties between the QSCC occurrence and the no-rain cases were demonstrated. In this subsection, the dependence of the intensity
and area of rainfall produced by QSCCs on the environmental conditions is investigated.

Figure 17 shows the relationships and correlations between the averaged precipitation intensity within the identified QSCCs and the environmental parameters. Although the correlation coefficients are small, positive (negative) relationships of the precipitation intensity with the thermodynamic parameters are found for CAPE, CIN, and TLR (SSI). The relationships between the precipitation intensity and the parameters CAPE, SSI, and TLR are reasonable, because stronger instability is related to stronger precipitation intensity. For the shear parameters (i.e. MS03 and EH03), there are negative relationships between the precipitation intensity and the parameters. The relationships of the precipitation intensity with CAPE, SSI, TLR, and MS03 indicate higher correlation.

The relationships between the precipitation area of the QSCCs and the environmental parameters are demonstrated in Figure 18. In contrast to the case of the precipitation intensity, the relationships between the precipitation area and the thermodynamic parameters seem inconsistent with the convective instability concept since, in general, the correlation coefficients are negligible. On the other hand, the relationships with the shear parameters indicate higher positive correlations. The highest correlation is seen for MS03.

From this analysis, it can be stated that convective instability has the strongest correlation with precipitation intensity within the QSCCs, and shear intensity is associated with the size of the precipitation area.

3.5. Characteristics of slower- and faster-moving systems

In this study, we have focused on convective clusters which we regard as quasi-stationary, i.e. those whose speed is less than or equal to 10 m s$^{-1}$. However, this speed may not be a suitable threshold; for example, Barnes and Sieckman (1984)...

Table 1. The mean, standard deviation, and T-value of the environmental parameters between QSCCs (Q) and no-rain cases (N).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Average (standard deviation)</th>
<th>T-value (Q–N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPE</td>
<td>J kg$^{-1}$</td>
<td>489 (554)</td>
<td>69.7 (236)</td>
</tr>
<tr>
<td>CIN</td>
<td>J kg$^{-1}$</td>
<td>44.1 (58.5)</td>
<td>24.5 (63.2)</td>
</tr>
<tr>
<td>PW</td>
<td>mm</td>
<td>47.4 (11.5)</td>
<td>23.1 (11.8)</td>
</tr>
<tr>
<td>SSI</td>
<td>°C</td>
<td>–1.9 (3.3)</td>
<td>1.4 (4.7)</td>
</tr>
<tr>
<td>KI</td>
<td>°C</td>
<td>30.7 (8.40)</td>
<td>7.98 (17.8)</td>
</tr>
<tr>
<td>TLR</td>
<td>K km$^{-1}$</td>
<td>5.31 (0.52)</td>
<td>5.29 (0.78)</td>
</tr>
<tr>
<td>MS03</td>
<td>×10$^{-4}$ s$^{-1}$</td>
<td>13.0 (7.83)</td>
<td>11.8 (6.23)</td>
</tr>
<tr>
<td>EH03</td>
<td>m$^{2}$ s$^{-2}$</td>
<td>47.2 (107)</td>
<td>10.9 (61.7)</td>
</tr>
</tbody>
</table>

* An asterisk indicates that the mean values of Q and N are significantly different at the 95% confidence level.
described a mesoscale convective cloud line whose speed is greater than 7 m s$^{-1}$ as a fast-moving line. Thus, in this subsection, we examine and compare the characteristics between slower-moving and faster-moving CCs.

Figure 19 shows the frequency distribution of the speed of the extracted QSCCs. A peak frequency is found at a speed of 6.0 m s$^{-1}$, and the mean speed, $v_{\text{mean}}$, is 5.6 m s$^{-1}$, indicating that the shape of the frequency distribution looks normal despite a slight shift to higher values. Thus, we divide the QSCCs into two sub-categories: slower-moving and faster-moving CCs depending on their speed in order to show the differences in their characteristics. Slower-moving CCs (denoted as S) are defined as clusters whose speed is less than $v_{\text{mean}} - 1\sigma$, where the standard deviation of the speed of the extracted QSCCs, $\sigma$, is 1.8 m s$^{-1}$. Among the 4133 QSCCs, the numbers of S and F cases are 706 and 718 respectively.

Firstly, the statistics of the temporal and spatial means of precipitation intensity and the temporal mean of precipitation area for each category are shown in Figure 20. Figure 20 shows the maxima/minima, medians, and 75 and 25 percentiles. Precipitation intensity is larger in S than in F (Figure 20(a)), while precipitation area is smaller in S than in F (Figure 20(b)). At the 95% confidence level, the precipitation intensity is significantly larger in S than in F, while precipitation area is significantly smaller in S than in F, i.e. the slower-moving CCs have a stronger intensity and a smaller horizontal size of precipitation than the faster-moving CCs.
Figure 16. Moisture content integrated over layers (a) 0–1 km, (b) 1–2 km, (c) 2–3 km, (d) 3–4 km, and (e) 4–5 km relative (%) to the precipitable water from radiosonde observations (all 11 sites) for QSCCs (Q, solid line) and no-rain cases (N, dashed line). The frequency intervals in (a), (b)–(d), and (e) are 5, 2.5, and 2, respectively. The values show the frequencies accumulated at the centre of the intervals.

Figure 17. The relationships between the mean precipitation intensity (mm h$^{-1}$) averaged in time and space for the QSCCs and (a) CAPE (J kg$^{-1}$), (b) CIN (J kg$^{-1}$), (c) PW (mm), (d) SSI (°C), (e) KI (°C), (f) TLR (K km$^{-1}$), (g) MS03 ($\times10^{-4}$ s$^{-1}$) and (h) EH03 (m$^2$ s$^{-2}$). The correlation coefficient between the precipitation intensity and the environmental parameter is given in each panel.
To see how the difference of the distributions in Figure 20 arises as a function of the environmental properties, Figure 21 compares the frequency distributions of the environmental parameters in S and F. Compared to F, S indicates a smaller amount of PW, a higher degree of instability (SSI, TLR, and CAPE), and weaker shear (MS03) with a smaller hodograph curvature (EH03).

Statistical significance of the differences of the mean values between S and F is examined with the test statistic $T$. Table 2 shows the values of test statistic $T$ for the environmental parameters. All the environmental parameters indicate statistically significant differences between S and F. It is seen that the S environment shows higher instability (SSI, TLR, and CAPE) and weaker shear (MS03 and EH03), but lower moisture (PW) than the F environment.

The monthly changes of CAPE, PW, and MS03 are shown in Figure 22 in a similar fashion to Figure 14. CAPE (MS03) is clearly larger (smaller) in S than in F, in a consistent manner with those shown in Figure 21 and Table 2, while PW has a larger monthly
Figure 21. As Figure 13, but for slow-moving (S, black) and fast-moving (F, grey) categories. The frequency intervals in (a)–(h) are 200, 50, 10, 3, 5, 1, 5 and 50, respectively. The values show the frequencies accumulated at the centre of the intervals.

Table 2. As Table 1, but for slow-moving (S) and fast-moving (F) cases.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Average (standard deviation)</th>
<th>T-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S</td>
<td>F</td>
</tr>
<tr>
<td>CAPE</td>
<td>J kg⁻¹</td>
<td>625 (564)</td>
<td>486 (550)</td>
</tr>
<tr>
<td>CIN</td>
<td>J kg⁻¹</td>
<td>50.4 (56.8)</td>
<td>37.1 (53.5)</td>
</tr>
<tr>
<td>PW</td>
<td>mm</td>
<td>47.8 (9.35)</td>
<td>49.4 (11.5)</td>
</tr>
<tr>
<td>SSI</td>
<td>°C</td>
<td>-2.9 (2.6)</td>
<td>-1.6 (3.2)</td>
</tr>
<tr>
<td>KI</td>
<td>°C</td>
<td>30.9 (7.39)</td>
<td>31.8 (7.83)</td>
</tr>
<tr>
<td>TLR</td>
<td>K km⁻¹</td>
<td>5.42 (0.44)</td>
<td>5.25 (0.51)</td>
</tr>
<tr>
<td>MS03</td>
<td>×10⁻⁴ s⁻¹</td>
<td>9.49 (5.73)</td>
<td>15.0 (8.26)</td>
</tr>
<tr>
<td>EH03</td>
<td>m² s⁻²</td>
<td>22.1 (69.7)</td>
<td>61.9 (121)</td>
</tr>
</tbody>
</table>

variation in F than in S. Thus, it is suggested that there are no consistent features in the PW variation on a monthly basis.

Overall differences for the precipitation intensity between S and F are the same as those between Q and N. This suggests that the environmental conditions for the slower-moving CCs are characterized by higher instability and weaker vertical shear. In contrast to the precipitation intensity, there are no discernible relationships between precipitation area and the environmental parameters (not shown).

From the analyses of environmental parameters for S and F, the physical interpretation of the results of Figures 20 and 21 are attempted here. Firstly, from the analyses of the relationships between environmental conditions and rainfall characteristics, it was found that the larger precipitation intensity is related to higher instability and to weaker shear intensity. The bulk Richardson number in S, estimated by using CAPE and a shear between the levels of 0 and 6 km (Table 2), is about 100, which corresponds to a condition for the development of multicell storms (Weisman and Klemp, 1982). Because the CAPE values for Q are considerably smaller than those for squall lines and supercell storms over the Great Plains of the USA (Bluestein and Jain, 1985), stronger shears as measured by the bulk Richardson number are detrimental to the development of convection even in the multicell category. Thus, a moderate value of the vertical wind shear is appropriate for the development of the slower-moving CCs, which are a type of multicell storm, in Japan.

It is noted that the smaller precipitation area in the slower-moving CCs associated with smaller MS03 can be attributed to the fact that the shape of shear determines the organization mode of MCSs (LeMone et al., 1998; Parker and Johnson, 2000). A stronger environmental shear is in general favourable for a more organized structure of MCSs (e.g. Weisman and Rotunno, 2004). In addition, the environmental shear also restricts the size and motion of convective cells within MCSs (e.g. Doswell et al., 1996). In other words, a weaker shear is detrimental for the organization of convection. Therefore, it is considered that a weaker shear condition identified for the slower-moving CCs leads to less organized and smaller CCs.

4. Summary and conclusions

The characteristics and environmental properties of QSCCs during the warm season in Japan were statistically investigated.
using weather radar and upper-air sounding data from JMA from May to October during 2005–2012. An algorithm developed by Shimizu and Uyeda (2012), called AITCC, was modified to identify QSCCs from radar data. We found 4133 QSCCs over the Japanese major islands.

Compiling numerous QSCC samples revealed that the average and maximum horizontal scales of QSCCs with a circular shape are about 20 and 72 km, respectively. Thus, QSCCs in Japan are regarded as meso-β-scale phenomena. Ninety-five percent of the extracted QSCCs have a lifetime of less than 60 min, and the number of longer-lived QSCCs rapidly decreases as the lifetime increases. QSCCs occur more frequently on the Pacific side of the Japanese islands and the inland regions in central Japan, which are associated with higher convective instabilities, more moisture, and intermediate shear intensities.

The analyses of the vertical profiles of temperature, water vapour mixing ratio, and horizontal winds between the QSCC and no-rain cases indicate that the temperatures below the 850 hPa level and above the 400 hPa level are larger in the QSCC cases than in the no-rain cases. It is also indicated that the moisture content throughout the troposphere is larger in the QSCC cases than in the no-rain cases. The shear profile indicates that there are pronounced differences in the meridional component between the QSCC and the no-rain cases; there is a southerly component in the QSCC cases and a northerly component in the no-rain cases, suggesting that the hodograph shape in the QSCC cases is related to the large-scale ascent. Although other conditions (e.g., an intrusion of the jet in the upper atmosphere) are required to induce the large-scale ascent, one possibility for the existence of the large-scale ascent is demonstrated in this study.

The environmental conditions for the occurrence of the QSCCs were further investigated using stability and shear parameters. Most of the examined thermodynamic parameters indicate that there is a significant difference in the stability condition of the QSCC and no-rain cases. The moisture contents not only at the lower levels but also at the middle levels (above the 2 km height) are significantly larger in the QSCC cases than in the no-rain cases. This moisture difference leads to differences in KI, SSI, and PW between the QSCC and the no-rain cases. The kinematic parameters indicated that both MS03 and EH03 significantly characterize the environmental conditions of the QSCC cases from the no-rain cases. From the diagnosis using the environmental indices, it is concluded that the amount of moisture in the lower layer controls the stability condition for the development of the QSCCs, and that the magnitudes of the wind shear and the helicity at the lower levels distinguish the kinematic environment for the development of the QSCCs.

In addition, the moisture content at each vertical level and its contribution to the total amount of moisture (i.e. PW) were also examined. An increase in the middle-level moisture leads to more PW in the QSCC environments. Considering that higher middle-level moisture controls the development of convection (Derbyshire et al., 2004; Kikuchi and Takayabu, 2004; Takemi et al., 2004; Kato, 2006; Takemi, 2015), atmospheric moistening before the development stage of convection plays an important role in the development of the QSCCs.

Examining the relationship between the precipitation intensity and area of the QSCCs and the environmental parameters shows that the precipitation intensity within the QSCCs during the warm season in Japan has a higher correlation with the convective instability (CAPE and SSI) while the precipitation area has a stronger correlation with the shear intensity (MS03).

The characteristics and environmental properties between slower- and faster-moving CCs were compared. Investigating the statistical significance of the differences in the means between the two categories indicates that the precipitation intensity is significantly larger in slower-moving CCs than in faster-moving CCs, while the precipitation area is significantly smaller in the slower-moving CCs. The analysis of environmental parameters suggests that the stronger precipitation intensity for the slower-moving CCs is due to a higher instability and a weaker shear intensity, whereas the smaller precipitation area is due to a weaker shear intensity.

QSCCs are widespread mesoscale phenomena, not only in Japan but also around the world. In generating QSCCs, complex topography should play an important role. The geography of Japan is characterized by complex terrain, and therefore the geographical features should have a significant impact on the occurrence of QSCCs. In addition, moister conditions characterize the environmental conditions for the occurrence of QSCCs in humid climates. From the numerical experiments conducted by Takemi (2014b), moister environments lead to the development of stronger and more organized CCs. The present study shows that middle-level moister conditions favour the occurrence of stronger precipitation intensity within the QSCCs. These results should contribute to the understanding of quasi-stationary or slow-moving convective clusters in those regions.

Furthermore, the present study demonstrates that operational data such as radars, upper-air soundings, and high-resolution gridded analyses provided by meteorological centres are very useful for investigating mesoscale convective phenomena and their environmental properties from a climatological point of view. Although we have previously conducted this type of study using operational meteorological data (Nomura and Takemi, 2011; Takemi, 2014a), the present study also confirms the usefulness of this approach. The outcome from our studies should provide basic information on the diagnosis of mesoscale phenomena.

Acknowledgements

We would like to thank Dr Shingo Shimizu at the National Research Institute for Earth Science and Disaster Prevention who provided the program of Algorithm for the Identification and Tracking of Convective Cells (AITCC). The constructive comments and suggestions by two anonymous reviewers and the chief editor, Proфессор J. Parker, are greatly acknowledged for improving the original manuscript. The operational radar dataset used in this study was provided by the Japan Meteorological Business Support Center. The upper-air sounding data used in this study were obtained from the Atmospheric Soundings web site (http://weather.uwyo.edu/upperair/sounding.html; accessed 28 December 2015) at the University of Wyoming. Convective available potential energy was calculated using the Fortran90 program obtained from the website of Dr George H. Bryan at the National Center for Atmospheric Research. The Generic Mapping Tools (GMT) were used for drawing some of the figures.

Appendix

Definition of SSI and KI

To assist the discussion on the relationships between the thermodynamic vertical profiles and environmental properties in sections 3.2–3.5, we will describe the definition of the Showalter Stability Index (SSI) and the K Index (KI) as

\[ SSI = T_{500} - T_{850} \]  
\[ KI = T_{850} - T_{700} + T_{500} - (T_{700} - T_{500}) \]

where \( T_{850}, T_{700}, \) and \( T_{500} \) are the temperatures at the 850, 700, and 500 hPa levels, respectively. \( T_{850} \) and \( T_{700} \) are the dew-point temperatures at 850 and 700 hPa, respectively, and \( T_{500} = T_{d500} \) is the temperature at 500 hPa of a parcel raised adiabatically from 850 to 500 hPa.

Supporting information

File S1. Figures provide the upper-air sounding data for the QSCCs and no-rain cases at all the sites and all the seasons. Tables exhibit the monthly mean values of CAPE, PW, SSI, and MS03 for the QSCCs at all the sites.

References


