Anomalous Weather Patterns in Relation to Heavy Precipitation Events in Japan during the Baiu Season

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ABSTRACT

Anomalous weather patterns (WPs) in relation to heavy precipitation events during the baiu season in Japan are investigated using a nonlinear classification technique known as the self-organizing map (SOM). The analysis is performed on daily time scales using the Japanese 55-year Reanalysis Project (JRA-55) to determine the role of circulation and atmospheric moisture on extreme events and to investigate interannual and interdecadal variations for possible linkages with global-scale climate variability. SOM is simultaneously employed on four atmospheric variables over East Asia that are related to baiu front variability, whereby anomalous WPs that dominated during the 1958–2011 period are obtained. Our analysis extracts seven typical WPs, which are linked to frequent occurrences of heavy precipitation events. Each WP is associated with regional variations in the probability of extreme precipitation events. On interannual time scales, El Niño–Southern Oscillation (ENSO) affects the frequency of the WPs in relation to the heavy rainfall events. The warm phase of ENSO results in an increased frequency of a WP that provides a southwesterly intrusion of high equivalent potential temperature at low levels, while the cold phase provides southeastern intrusion. In addition, the results of this analysis suggest that interdecadal variability of frequency for heavy rainfall events corresponds to changes in frequency distributions of WPs and are not due to one particular WP.

1. Introduction

Extreme climatic events such as droughts, heat waves, and floods are potentially devastating, with serious implications for individuals, ecosystems, and societies. Human activities and the environment are greatly affected by such climatic extremes. During the rainy monsoon season (early summer) in Japan, heavy rainfall events frequently occur, owing to the intrusion of warm humid air into a stationary front known as the baiu–mei-yu–changma (hereafter baiu for short) front. Many heavy rainfall events correspond with the intensified baiu front that causes flooding and serious damages to human life and properties. Early prediction and warning for heavy rainfall events are among the most important elements for minimizing damages. However, it has always been difficult to accurately forecast rainfall owing to imperfection of global models and observational errors. Development of a forecasting system for extreme events continues to be a challenging task in spite of recent rapid developments for data assimilation and for numerical prediction models. Heavy rainfall events can have various atmospheric origins (e.g., convective rainfall and frontal rainfall) and may be nonlinearly related to many meteorological factors. Synoptic-scale background conditions are one of the dominant origins of continuous heavy rainfall. Classification of such synoptic-scale conditions can be potentially fruitful for understanding the origin of extreme events and improving rainfall forecasting. For example, weather pattern (WP) classification at the synoptic scale has been useful for characterizing statistical properties of climatic records, such as precipitation series, at the local scale (e.g., Brigode et al. 2013). In this framework, recent studies (e.g., Garavaglia et al. 2010, 2011) have used WP subsampling and probability distribution with a hydrological model to predict floods.
from extreme rainfall events. Moreover, potential interannual to interdecadal changes in extreme events are of particular concern since these tend to have the greatest economic and social consequences. Global-scale climate variations such as those associated with El Niño–Southern Oscillation (ENSO) can affect regional-scale climates through the change in WP frequency of occurrence. For example, several studies showed significant correlation between WP frequency and ENSO climate signals around the northern Pacific (e.g., Kimoto and Ghil 1993), which can result in dramatic changes in regional climates. Recent studies also demonstrate the existence of a link between the frequency of occurrence of extreme events and ENSO-related WPs (e.g., Casola and Wallace 2007). Identification of the WP associated with the extremes enables us to determine the physical mechanisms by which precipitation extremes are impacted by global signals. In this context, the WP classification can be a bridging tool between climate signals and local extreme rainfall.

The relationship between frequency of heavy precipitation and anomalous WP is complex, especially in the East Asia, because climate is intricately affected by global-scale climate modes such as the Asian monsoon, ENSO, and Arctic Oscillation. The climate variability in the tropical Pacific and Indian Ocean strongly affects the East Asian summer climate such as precipitation (e.g., Ohba and Ueda 2006; Xie et al. 2009; Kosaka et al. 2013) and the routes and genesis of typhoons (e.g., Du et al. 2011; Yonekura and Hall 2014). In this framework, precipitation in Japan during the baiu season represents a very interesting playground, and therefore, links between rainfall over the region and large-scale climatic phenomena are the emphasis of scientific research (e.g., Wu et al. 2003; Yamaura and Tomita 2012). These previous studies suggest climate mode variability and seasonal rainfall behavior may correlate over East Asia. However, scientific questions about the link between the heavy precipitation in Japan and WPs remain unanswered.

When classifying various WPs, an artificial neural network learning mechanism can be an effective tool for classifying various WPs. One of the widely used nonlinear classification techniques, self-organizing map (SOM), is an artificial neural network. SOM is a pattern recognition technique, developed by Kohonen (1982) that is capable of projecting high-dimensional data to a visually understandable two-dimensional map. Several advantages of this methodology have been described, including a powerful visualization approach (Reusch et al. 2007; Leloup et al. 2007; Sugimoto and Tachibana 2008; Iseri et al. 2009). Since a spatially organized set of patterns of variability of the data are obtained from SOM, it has been used in many fields, such as for oceanographic studies (Leloup et al. 2007; Tozuka et al. 2008; Johnson 2013), climate characterization over the Northern Hemisphere (Reusch et al. 2007; Johnson and Feldstein 2010), identification of spatially varying systematic numerical model errors (Kolczynski and Hacker 2014), global climate model evaluations (Radić and Clarke 2011), rainfall prediction in the monsoon systems (Cavazos et al. 2002; Chattopadhyay et al. 2008; Chu et al. 2012), and examination of the relationship between synoptic fields and rainfall events (Cavazos 1999; Nishiyama et al. 2007; Cassano et al. 2007; Polo et al. 2011; Singh et al. 2014). In these studies, visually clear-cut climate mode and weather patterns have been successfully extracted from complicated (nonlinear) data. The SOM technique is, therefore, potentially useful for identifying complicated nonlinear interrelationships among meteorological factors associated with heavy rainfall events.

In this study, we apply the SOM approach to investigate well-known but complex relationships between synoptic WPs and heavy rainfall events during the baiu season. We classify nonlinear patterns of synoptic WPs during the rainy season in East Asia and identify typical synoptic WPs closely related to heavy rainfall events in Japan. This WP approach is also used to study the interannual and interdecadal change of the links between WPs and heavy rainfall events in Japan. This paper is organized as follows. Section 2 contains a description of the data and method utilized in the present study. Section 3 examines a classification of extreme precipitation patterns around Japan. Section 4 represents the interannual and interdecadal variation of the heavy rainfall WPs. Finally, we summarize our conclusions in section 5.

2. Data and analysis method

a. Data

Atmospheric data for the period 1958–2011 used in this study were taken from the Japanese 55-year Reanalysis Project (JRA-55; Ebita et al. 2011). The atmospheric variables were available at standard pressure levels with a horizontal resolution of 1.25°. We used air temperature, horizontal wind, geopotential height, and specific humidity. This study focuses solely on daily precipitation because of its long record. We use historical high-resolution (0.05° × 0.05°) daily precipitation data over the Japanese land from the Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project, which is referred to as APHRO_JP. This product is derived from rain gauge observations and is intended to accurately represent both mean and extreme values; details of the data are documented in
The product has two versions, one of which is produced from all available rain gauge data (i.e., the main source of data in this study), and another that is derived from only 60 stations that have continuous records since 1900. Only data from the boreal early summer (from 1 June to 31 July) are used because it is the period of most intensive rainfall (known as the baiu season) in Japan. Figures 1a and 1b, respectively, show the climatology and standard deviation of the precipitation used in this study. Both the mean precipitation and the extremes during the baiu season are relatively large in western Japan during this season. As supplementary rainfall data, we also use the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin 1997). The Extended Reconstructed Sea Surface Temperature, version 3 (ERSST.v3; Smith et al. 2008), dataset was also used for analysis.

In this study, heavy rainfall days are defined when at least one grid box experiences 150 mm day$^{-1}$ of precipitation. Precipitation exceeding 100 or 150 mm day$^{-1}$ is often used for the definition of heavy rainfall events (e.g., Goswami et al. 2006). We used 150 mm day$^{-1}$ as a threshold to define a heavy rainfall event because about 15% of all days in the record have at least one grid point with 150 mm of rainfall occurrence over a 24-h period. The precipitation data can be used to determine heavy precipitation up to approximately 150 mm day$^{-1}$ for statistical extremes analysis (Kamiguchi et al. 2010).
We simultaneously apply SOM to daily-mean variables derived from JRA-55, as conducted in combined EOF analysis (Wang 1992; Nakazawa and Rajendran 2007). We selected four atmospheric variables as input for SOM: 850-hPa equivalent-potential temperature $\theta_e$, 850-hPa zonal and meridional wind, and 200-hPa geopotential height GH anomalies. The variable $\theta_e$ is a thermodynamic parameter involving both temperature and humidity, and its low-level advection to the region from the tropics can significantly intensify rainfall over the baiu front. Previous studies (e.g., Ninomiya 2000; Ninomiya and Shibagaki 2007) for the baiu front suggest that advection of an equivalent potential temperature that consists of a poleward moisture flux by the low-level jet and cold air advection by the upper-level jet are important to the active baiu rainband. In addition, Yoshikane et al. (2001) reported that the baiu rainband is quite sensitive to not only the low-level jet, but also the positions (and meandering) of the upper-level jet stream, which is significantly influenced by 200-hPa GH.

The analyses are conducted within a specific region (22.5°–50°N, 120°–155°E) for the period of 1958–2011. Anomalies were identified by removing a mean climatological cycle and then normalized with respect to each variable so that each variable receives equal weight in the SOM analysis. The climatological cycle was defined with the entire 1958–2011, and a 5-day running average was applied to reduce day to day variation. The anomalies were area-weighted to account for the increasing grid point density with latitude and were standardized by a domain-integrated standard deviation. Sensitivity to the choice of input was also tested by using other variables (such as 500-hPa GH, 850-hPa GH, and 200-hPa wind). The blend of the four selected variables shows relatively strong localization of heavy precipitation frequency (exceeding 150 mm day$^{-1}$) within SOM nodes, implying that the use of this blend is suitable for identifying WPs that frequently provide heavy rainfall in Japan.

b. SOM technique

In this study, the four input fields (i.e., normalized 850-hPa $\theta_e$, zonal and meridional wind, and 200-hPa GH anomalies) of standardized anomalies for each day are concatenated into an $N$-dimensional vector ($N$ is 4 times the number of grid points in the domain) as input vector. These daily vectors (input vectors) are projected onto regularly arranged two-dimensional arrays referred to as SOMs. Each of the elements in the SOM array is denoted as a node (or neuron), which has one reference vector. For example, a 10 $\times$ 10 grid SOM has 100 reference vectors on the SOM and the map is composed of 100 nodes. The reference vector has the same dimensions as the input vector and represents a generalized pattern of input vectors. The number of all input vectors is 3294 (61 day $\times$ 54 yr) in this study. As for the initial value of reference vectors, random vectors are used. The neighborhood region is also defined as nodes surrounding the winning node that covers all the nodes in the first step. First, each input vector will be compared with all reference vectors. The best-matching (i.e., winning) node is identified by computing the Euclidean distance between the selected input vector and all reference vectors. After the winning node is identified, both the winning and neighborhood nodes will be updated by the input vector. This process is repeated for each input vector for a large number of cycles with the gradually decreasing neighborhood region. Finally, each SOM pattern is approximately the mean of all daily data vectors assigned to the SOM pattern. The reference vectors that are located relatively nearby on the map exhibit a similar representative pattern (i.e., data structure of reference vector), whereas distantly located reference vectors exhibit a relatively dissimilar pattern. Thus, SOM classifies input data into a two-dimensional plane utilizing similarities with the extracted patterns (reference vectors) on the map. For more details, one can refer to other recent studies (Hewitson and Crane 2002; Richardson et al. 2003; Liu et al. 2006; Johnson et al. 2008).

While SOM is an effective platform for visualization of high-dimensional data, the method cannot find an appropriate number of well-defined clusters because there are many groups of nodes with similar characteristics that potentially form clusters and therefore are not easy to interpret (Vesanto and Alhoniemi 2000). The additional clustering is often applied to fully exploit the properties of the dataset (e.g., Leloup et al. 2007). Vesanto and Alhoniemi (2000) proposed a two-level clustering approach by which the SOM nodes are clustered again with a further cluster technique. This study employs the similar two-level approach. According to Ward’s hierarchical clustering method (Ward 1963), the SOM nodes are additionally clustered into groups, similar to a study conducted by Leloup et al. (2007). This hierarchical clustering method seeks to form the partitions in a manner that minimizes the loss associated with each grouping, by seeking cluster pairs whose fusion results in minimum Euclidean distance at each step. There is no rule to determine the “optimal” number of nodes in SOM. The SOM adopted in this study consists of 12 $\times$ 12 neurons (i.e., 144 WPs). Datasets should be reduced into a moderate-sized map, not only for consideration of calculation efficiency, but also to provide sufficient representation of patterns to extract all
characteristic patterns. The most suitable map size is found by carrying out several tests including testing map sizes of $14 \times 14, 10 \times 10, 8 \times 8,$ and $6 \times 6.$ A $12 \times 12$ map size had a relatively low root-mean-square error (RMSE). Random subsets with 80% of the data were also used to test the reproducibility of the classification. Differences between the extracted SOM patterns were relatively small, which suggests that the classification has a good repeatability.

3. Weather patterns during the baiu season

The baiu front is a well-known phenomenon embedded in the Asian summer monsoon, which is a high-impact weather system and plays an important role in water resources. Figure 1c shows the climatological June–July mean precipitation, which is represented by climatological monthly-mean rainfall obtained from CMAP. In the Yangtze River valley of China and central Japan, the baiu front commences in early boreal summer, during which a zonally elongated rainband covers China, Korea, Japan, and the northwestern Pacific along $30^\circ$-$40^\circ$N (Fig. 1c). Research on the baiu front (e.g., Chen and Chang 1980; Kodama 1992; Ninomiya and Shibagaki 2007) shows that the rainband forms on the northern boundary of a warm moist air mass in the subtropics. Moisture is transported by southwesterly flow along the western rim of the North Pacific subtropical high, which feeds the rainband. Heavy rainfall is occasionally observed in the rainband, with midtropospheric warming and moistening as a consequence of active cumulus convection (e.g., Ninomiya and Shibagaki 2007). Figure 1d shows the climatological synoptic-scale features in the season (June–July mean). The baiu front is basically characterized by the 330K line of the 850-hPa $\theta_e$, and is regarded as a “subtropical front” characterized by a thick moist layer (Ninomiya 1984). Both warm air and moisture advection from the south are important for the formation of the baiu front (Sampe and Xie 2010). A large amount of warm moist air intrudes into the Japan region during the baiu season as part of the low-level southwesterly flow. Frequently, the baiu front is intensified by the atmospheric fields that allow for heavy rainfall events. However, because the baiu season consists of many kinds of WPs, it is difficult to assess whether a given WP will produce heavy rainfall. Therefore, the WP classification can be helpful for capturing the relationship.

Relationships between the WPs and heavy precipitation in the region are identified by areas experiencing more than 150 mm day$^{-1}$ of heavy precipitation (Fig. 2a). We can find relatively high frequencies (i.e., exceeding 30% of the total frequency of each WP node) of heavy precipitation mainly in the left, top-right, and bottom-right of the SOM. We identify 28 clusters of SOM nodes, seven of which are associated with frequent heavy rainfall (Fig. 2a; black line; the other clusters are neglected here to facilitate the visualization). Figures 2b–h illustrate the reference vectors (WPs) extracted from each cluster (Clst). Red (blue) shaded contours indicate relatively high (low) $\theta_e$ at the 850-hPa level, and green vectors represent the 850-hPa wind. Areas of high pressure at the 200-hPa are presented by solid contours. Anomalous positive $\theta_e$ intrudes into the islands of Japan from various directions, including west (Clst5), southwest (Clst1 and Clst4), south (Clst2 and Clst6), and east (Clst3 and Clst7). About 60% of 150 mm day$^{-1}$ occurrences are accounted for by the seven clusters, which account for about 18% of all analyzed days. Although many heavy rainfall events depend on the large-scale atmospheric condition, there exists localized torrential heavy rainfall embedded within large-scale regions of lower-precipitation intensity. The typical characteristics of such localized torrential rainfall are random occurrence, small horizontal scale, and a short lifetime. While the latter is also very important, this study focused principally on the former rainfall events.

The cluster-averaged daily-mean WPs are shown in Fig. 3. The high-$\theta_e$ region for Clst1 extends from south to northeast of Japan. Northeastward intrusion of warm moist air is mainly attributed to low-level high pressure in the southeast of Japan, while 200-hPa GH reveals eastward-propagating Rossby wavelike patterns. Japan is covered by warm moist southerlies in Clst2 that correspond with the low-level cyclone system located to the west of Japan. Both Clst3 and Clst4 show the Pacific–Japan (PJ; Nitta 1987) pattern-like WPs (they have opposite phases). Japan is sandwiched between high and low-pressure anomalies in both patterns, but the position of the PJ-like pattern in Clst4 is slightly shifted eastward $10^\circ$–$15^\circ$ in longitude relative to Clst3. Clst5 is also almost opposite to Clst3 (and relatively similar to Clst4), but the high $\theta_e$ extends a long way from the west to the east of Japan. The western region of Japan is covered by low-level westerly winds with intrusion of warm moist air. Clst6 is relatively similar to Clst2, whereas the low in the west-southwest of Japan is coincident with the northward intrusion of very high $\theta_e$ that is associated with extratropical/tropical cyclone. Clst7 could correspond to cyclonic circulation anomalies over the Sea of Japan that provide for the intrusion of cold dry (warm moist) air to the west (east) of Japan. Among the seven clusters, Clst7 is unique since it does not involve the positive $\theta_e$ anomalies over Japan. It could be conceivable that the strong upper-level low to the west...
of Japan destabilizes the mid- and upper levels, promoting deep convection even without the anomalous positive \( u_e \).

Spatial distribution of cluster-averaged precipitation anomalies and frequency occurrence of 150-mm daily rainfall in Japan are presented in Figs. 4a and 4b, respectively, and clearly show the differences in the effect of each WP. The WPs of Clst1 and Clst4 have the greatest influence on precipitation on the Sea of Japan side on the west of Japan, while those of Clst2 and Clst6 more strongly influence the Pacific side. The effect of the WP of Clst5 on local precipitation is relatively limited to the western edge of the Japanese islands (Kyushu region), whereas the WPs of Clst3 and Clst7 mainly affect eastern Japan. The difference in the effects of WPs on the composite anomalous local rainfall is also reflected in the spatial distribution of 150 mm day\(^{-1}\) frequency of occurrence (Fig. 4b).

The relationship between the WPs and heavy rainfall represents a significant regional difference, potentially due to topography, which is one of the important geographical features. Regionally dependent impacts of the WPs are shown using four different regions and the occurrence ratio of each WP in the top 50 events defined by the maximum daily precipitation for the past 54 years (Fig. 5). The seven WPs relevant to heavy rainfall account for 60%–70% in these areas, implying that the patterns are likely the dominant cause of heavy rain in the Japan region. The probability of heavy rainfall to each WP significantly differs in the region. Several heavy rainfall events associated with the baiu front occur in the
Kyushu Islands (western edge of Japan) every year, where Clst1 is the most dominant WP and Clst2 and Clst3 are subdominant. The Chugoku region is relatively similar to the Kyushu region, but Clst4 is the most dominant WP. The island of Shikoku, especially the southern part, also frequently experiences heavy rainfall similar to the Kyushu region. Events mainly correspond to Clst2 and Clst6 WPs that provide southward intrusion of high $\theta_e$. In contrast to the conditions of western Japan, Clst3 is dominant in the Kanto region, which exists in eastern Japan.

4. Interannual and interdecadal variability of the weather patterns

Anomalous convection associated with ENSO has a significant impact on the East Asian climate, according to numerous previous studies (e.g., Wang et al. 2000; Kosaka et al. 2013). Because ENSO is the most dominant climate mode of interannual variability in global climate, we assess the impact of ENSO events on the frequency of heavy rainfall WPs. There are several studies showing that summer precipitation in East Asia...
is affected greatly by ENSO (e.g., Chang et al. 2000; Wang et al. 2001; Xie et al. 2009). Wang et al. (2001) suggested that the influence of ENSO on the East Asian summer rainfall varies with the phase of an ENSO cycle. During the transition phase from El Niño to La Niña, the summer monsoon convection is suppressed along 10°–20°N in the western Pacific and enhances rainfall along the baiu front. This anomalous condition can be attributed primarily to the impact of delayed warming of the Indian Ocean with respect to El Niño (Ohba and Ueda 2006; Xie et al. 2009).

June–July mean values of the Niño-3.4 index for the period 1958–2011 are defined by the SST averaged over the region extending from 5°N to 5°S and 120° to 170°W. El Niño (La Niña) events are defined when the index exceeds (falls below) plus one (minus one) standard deviation in the period. Figure 6 presents the frequencies of the seven estimated WPs, where orange and blue dots show the frequency observed on El Niño and La Niña summers, respectively. Frequency is also illustrated with red and dark blue dots in Fig. 6 for the top five strongest El Niño (1965, 1972, 1987, 1991, and 1997) and
La Niña (1973, 1975, 1988, 1999, and 2010) cases, respectively. Frequency changes are more likely to be caused by ENSO when they are outside of the box plots (25%–75% percentiles). Significant changes are observed for Clst3 and Clst4 that correspond with La Niña and El Niño, respectively. WPs of Clst1 and Clst4 are much more common during the El Niño summers; however, WPs of Clst3 and Clst6 are more frequent in the La Niña summers.

Frequent occurrence of Clst1 and Clst4 can result in the intrusion of warm moist air from the southwest of Japan. Figure 7 presents the spatial distribution of precipitation frequency anomalies associated with ENSO. Warm moist air intrudes into Japan from the west of the region as a result of an increase in Clst4 in the El Niño composite. Precipitation rate (and risk of heavy precipitation) increases especially in western Japan and on the Sea of Japan side of eastern Japan. Frequency of 100 mm day$^{-1}$ precipitation increased during El Niño (La Niña) years, especially in the Kyushu and Chugoku regions (Fig. 7c). The spatial distribution of rainfall rate in the La Niña composite is almost opposite to the El Niño composite in eastern Japan, while it is not symmetric in western Japan (Figs. 7a,b). This result may be due to the increase of Clst6, potentially resulting from a northwestward shift in location of origin for tropical cyclones during the La Niña years (Yonekura and Hall 2014).

Figures 6 and 7 indicate that El Niño and La Niña events potentially result in an increased frequency of heavy rainfall WPs over different regions of Japan. In particular, El Niño (La Niña) events correspond to patterns with enhanced frequency of heavy rainfall in the southwestern (northeastern) part of Japan. Most WPs with enhanced frequencies during El Niño (La Niña) are Clst4 (Clst3), which could be related to the PJ pattern activated from the tropical western Pacific. Thus, the results of this analysis support a previously reported relationship between El Niño (La Niña) events and a positive (negative) phase of the PJ pattern (e.g., Kosaka et al. 2013); however, the atmospheric response is nonlinear, especially in the tropical western Pacific (Ohba and Ueda 2009; Ohba 2013). It is worth noting that most of the top five strong El Niño and La Niña events also correspond to years of the anomalous zonal SST gradient between the tropical Indian Ocean and Pacific Ocean, which often appears at the transition from the opposite ENSO phase in the preceding seasons (1965, 1972, 1973, 1988, 1999, and 2010). Recent studies (e.g., Ohba and Ueda 2006; Xie et al. 2009; Kosaka et al. 2013) have emphasized that the SST gradient is regarded as lagged ENSO response and is due to the delayed warming or cooling of the Indian Ocean (e.g., Klein et al. 1999; Ohba and Ueda 2005) and transition of ENSO from the winter to the following summer. The delayed Indian–Pacific Ocean anomalous SST gradient significantly affects the northwestern Pacific climate, including the modification of the baiu front activity. Therefore, it could be conceivable that the change in frequency of heavy precipitation is not only affected by the Pacific SST forcing.

As represented above, ENSO may have a much greater impact on short-term variations than long-term trends. In addition to the short-term variations, some
previous studies show the long-term linear trends of extreme precipitation frequency in the twentieth century. Fujibe et al. (2005, 2006) analyzed observational 4-hourly precipitation data over 100 years in Japan and showed an increase in frequency of heavy precipitation and a decrease in frequency of weak precipitation. The frequency–intensity of the extreme climate events will likely change more rapidly than the mean climate and will be felt most strongly through changes in intensity–frequency of climate extremes. The projected change in extreme precipitation is mainly attributed to the change in atmospheric motion (dynamic change) and moisture content (thermodynamic change). In climate model simulations, long-term increases in extreme precipitation under a global warming scenario are due to thermodynamic change over many parts of mid- and high latitudes, and therefore, dynamic change plays a secondary role (e.g., Emori et al. 2005; Cassano et al. 2007). However, on an interdecadal time scale, dynamic change could also contribute to the decadal variability of extreme precipitation frequency in addition to gradual thermodynamic change in relation to ongoing global warming. In this section, we also investigate the interdecadal variability of East Asia over the period to examine the changes in the SOM frequency distribution of heavy rainfall WPs.

To evaluate the long-term changes in the frequencies of occurrence, the frequency of occurrence of each WP for each year is smoothed by using a 5-yr moving average. Figure 8a illustrates the smoothed frequency time series for seven WPs. While the seven WPs occurred throughout the entire period, the frequencies of occurrence varied throughout the period. In particular, we can find a dominance of the Clst7 until the late 1970s, and then a dominance of Clst3 and Clst4 around the late 1980s and late 1990s, respectively. Total frequency of WPs did not show the significant trend.
Figure 8b shows the frequency of 150 mm day$^{-1}$ events obtained from the precipitation data. Since the precipitation data are interpolated from the observational data, its long-term trend could be affected by the historical increase in the number of rain gauge observation points. We additionally plot it from different versions of the precipitation data that are interpolated by using only 60 stations with continuous records through the period (Kamiguchi et al. 2010). After 1977, when Automated Meteorological Data Acquisition System (AMeDAS) deployed, the quality of the precipitation data was significantly improved. Available rain gauges were increased greatly in number up to more than 1100 because of installation of the observation network. Therefore it is difficult to discuss the long-term change by only using the data because its quality is not constant [readers can refer to Fig. 1 in Kamiguchi et al. (2010)]. On the other hand, the dataset with 60 stations is better suited for trend analysis and so on, although there are some problems, such as underestimation of the frequency of heavy rainfall occurrence.

Increase of heavy precipitation days is evident in Fig. 8b (gray bar and red line), but times at which rain gauge stations are limited (dark bar and blue line) are not evident. WP tended to dominate with the increase of heavy rainfall events over time intervals of about 10 yr (Figs. 8a,b). Around the year 1985, Clst4 dominated, though Clst2 is also frequent. Clst4 is characterized by intrusion of anomalously high $u$ by the enhanced Ogasawara high, whereas Clst2 features anomalous low (high) pressure over the west (east) of Japan that provides southerly wind over Japan. This notable change in the baiu rainfall after the 1970s could be closely associated with the regime shift of the SST variation in the eastern tropical Pacific and tropical Indian Ocean (Gong and Ho 2002). The following period, from 1995 to 2000, is characterized by early dominance of Clst4 and later dominance of Clst3. During the final period (since the late 2000s), the frequency of Clst5 and Clst2 become more prevalent. The correlation coefficient between the combined frequency of the seven cluster and the red (blue) line is 0.61 (0.41) during 1977–2011 (1958–2011), which is statistically significant at 95% (90%) confidence level. Thus, from this result, we can conclude that interdecadal variability of the frequency of heavy precipitation events correspond with changes in the frequency distribution of WPs that fluctuate on daily to weekly time scales. Very interestingly, the decadal variations are likely caused by multiple WPs and cannot be attributed to one specific WP.
5. Discussion and conclusions

Precipitation exhibits significant variability during the baiu season in Japan. Well-known but complex relationships between synoptic patterns and heavy rainfall events are systematically and visually investigated to understand these synoptic fields around Japan. They are classified using the SOM algorithm in combination with clustering techniques. Synoptic field patterns are expressed by the spatial distribution of 850-hPa $\theta_e$, horizontal wind, and 200-hPa GH. Occurrence of heavy rainfall can be attributed to seven clustered WPs from synoptic fields, which revealed different representative synoptic situations. The enhanced baiu front had anomalous anticyclonic or cyclonic flows around/over Japan, with high-$\theta_e$ intrusion accompanied by anomalous low-level wind.

The results of the analysis also document that there are regional differences in the synoptic circulation associated with extreme events in the study area. The neural network model, utilized in this analysis, is robust for analysis on regional climate and weather variability and, in particular, for investigating WPs corresponding with extreme events. In addition, the combination of four variables is effective for extracting a pattern related to heavy rain, implying that both the upper- and low-level flows are important for baiu rainfall intensity variation. From these results, we conclude that the SOM technique can be an effective tool for classifying complicated nonlinear synoptic fields and, in some cases, identifying precursors to extreme events.

ENSO episodes generally correspond with frequent occurrence of the particular WPs on interannual time scales. ENSO significantly influences the frequency of occurrence of two WPs: Clst3 is more common during La Niña rather than during El Niño and Clst4 is clearly more common during El Niño rather than during La Niña. This result is consistent with findings of previous studies showing that ENSO significantly influences precipitation patterns in East Asia. Empirical evidence of ENSO influence on rainfall characteristics (spatial distribution of rainfall rate) has been presented. Differences in the spatial distribution of rainfall over Japan are also apparent between El Niño and La Niña, which also probably affects the differences in the hydrological cycle (e.g., water resources and flood magnitudes).

The frequency of heavy rainfall in Japan shows interdecadal variation in the past 54 years. In this study, we demonstrate that the interdecadal variability in the WPs is related to the change in frequency of heavy rainfall. A decade-to-decade shift in the dominance of the WPs is also a factor in the interdecadal variation of heavy precipitation frequency. Interdecadal change in heavy precipitation could be caused by multiple WPs and, therefore, not be caused by the decadal change in the occurrence of a single WP. These results suggest that interdecadal variability over the East Asian climate involves not only changes in the mean basic state but also changes in the day-to-day evolution of synoptic weather that significantly affects frequency of local heavy precipitation.

Finally, these results open interesting perspectives in the fields of climate change impact prediction on heavy rainfall distribution, where WP classifications could be a bridging tool between climate model outputs and local rainfall observations. Classification of future WP projections by climate models could contribute to the evaluation of change in the heavy rainfall frequencies. Such empirical downscaling methods based on SOM can offer an inexpensive solution that can be quickly employed with a broad range of multimodel ensemble outputs that are regarded as the aggregate of day-to-day weather patterns. This will be done in a future study. It can also be useful for risk management in a specific area (e.g., hydroelectric and flood-control dams). In general, synoptic-scale processes have a predictability of several days. However, potential end users require high-resolution forecasts of surface variables, such as precipitation, to feed their models. For example, river discharge is a complex process involving slow response reservoirs and rapidly evolving precipitation fields. Since spatial resolution of global models is low (20–200 km), they cannot directly predict local rainfalls that are of the greatest relevance to users of the information. The identification of heavy rainfall phases using the SOM approach will be useful as an information source for decision making by climate–weather forecasters or end users engaging in disaster-proofing activities to reduce the risk of heavy rainfall.

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