Heavy Precipitation over Southwestern Japan during the Baiu Season due to Abundant Moisture Transport from Synoptic-Scale Atmospheric Conditions

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Abstract

Heavy precipitation frequently occurs over Kyushu, southwestern Japan, during the Baiu season, and abundant moisture transport is a key driving factor. To statistically understand the intensification of moisture transport to Kyushu during the Baiu season, synoptic-scale atmospheric conditions are examined using a composite analysis of reanalysis data. A heavy precipitation day is defined as a day with area-averaged daily precipitation over Kyushu that is larger than 1.0 mm and ranked in top 10% during May 31 to July 19 from 1981 to 2015. During such heavy precipitation days, the precipitation observed over Kyushu exceeds 100 mm day^{-1}. For several days before the occurrence of heavy precipitation over Kyushu, a plateau-scale disturbance develops over the Tibetan Plateau associated with daytime surface heating, and is characterized by cloud convection formation and eastward extension. During the eastward extension, latent heating from the cloud and upper-level high potential vorticity maintains the disturbance. The disturbance reaches northwest Kyushu on the heavy precipitation day, and a pair of positive and negative anomalies of relative vorticity over northwestern and southeastern Kyushu intensify the anomalous moisture transport.

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1. Introduction

During the Baiu season (the early summer rainy season in Japan), heavy precipitation events frequently occur over Kyushu, a southwestern island of Japan (Fig. 1a). The regional- and local-scale topography, including the mountains over Kyushu, the coastline of Kyushu Island, and the small islands around Kyushu, plays an important role in the formation and maintenance of band-shaped squall lines, which strongly affect continuous heavy precipitation occurrence within the Baiu rain band (Kato 1998; Yoshizaki et al. 2000; Adachi et al. 2004; Kato 2005). Evaporation from the Western Pacific supplies water vapor to the Baiu rain band, which leads to heavy precipitation (e.g., Akiyama 1973), and an intrusion of dry air in the mid-troposphere intensifies convective instability and rainfall (e.g. Kato 2006). Synoptic-scale moisture transport to the Baiu rain band is also a key factor in the heavy precipitation. Recent studies using a nonlinear classification technique known as the self-organizing map indicate that a convergence of synoptic-scale warm and moist southwesterlies along the northwestern edge of the North Pacific Subtropical High (NPSH) is favorable for heavy precipitation occurrence over Kyushu (Ohba et al. 2015; Nguyen-Le et al. 2017).

Plateau-scale disturbances coupled with cloud convection form over the Tibetan Plateau (TP) during summer because of several factors. These include daytime strong surface heating, moisture inflow to the plateau region, and moisture from the ground (Tao and Ding 1981; Wang 1987; Yasunari and Miwa 2006; Sugimoto and Ueno 2010). The disturbances sometimes propagate to the east (Li et al. 2008; Feng et al. 2014) and cause flooding of the Yangtze River (Xie and Ueno 2011). In case studies, the eastward propagation of the plateau-scale disturbances has been shown to enhance moisture inflow on the eastern side of the disturbances and to affect the development and/or regeneration of cloud convection along the Meiyu/Baiu front (Yasunari and Miwa 2006). An increase in precipitation over Kyushu has also been noted when the meso-scale convective system moves from the eastern edge of the TP (Akiyama 1984; Ninomiya et al. 1988; Chang et al. 1998). Thus, disturbances associated with cloud convection generated over the TP are important systems for anomalous moisture transport and heavy precipitation occurrence over Kyushu. However, a statistical investigation of the relationship between disturbances over the TP and heavy precipitation over Kyushu has not yet been reported.

Long-term high-quality reanalyses and observations covering more than 30 years are available, which permits a statistical composite analysis of synoptic-scale atmospheric conditions that cause extreme events, such as heavy rainfall occurrence. In this study, synoptic-scale conditions during heavy precipitation events over Kyushu in the Baiu season are investigated, with a focus on abundant moisture transport. Heavy precipitation events over Kyushu are detected using the observed precipitation. The time evolution of synoptic-scale atmospheric conditions causing heavy precipitation is examined using reanalysis data. Finally, the relationship between the eastward propagation of disturbances generated over the TP and heavy rainfall over Kyushu is discussed.

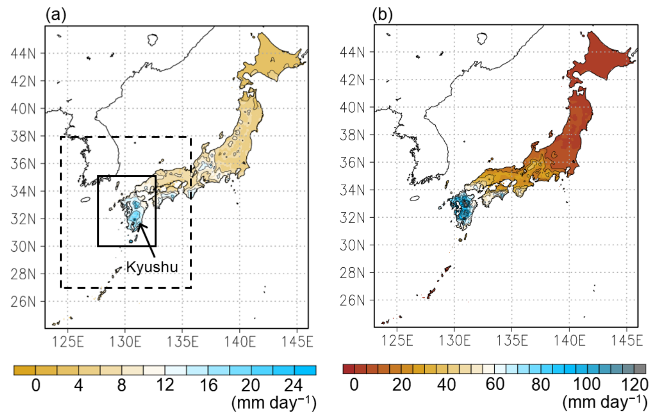

Fig. 1. Spatial distributions of (a) climatological daily precipitation between May 31 and July 19 from 1981 to 2015 and (b) composite daily precipitation on heavy precipitation days. Contour intervals are 4.0 mm day^{-1} for (a) and 10.0 mm day^{-1} for (b). White colors indicate no data are available. The rectangular land area enclosed by a solid black line was used to calculate the area-averaged precipitation over Kyushu. The rectangular area enclosed by a dashed black line was used for the confirmation of typhoon existence.

2. Method and data

Heavy precipitation over Kyushu and how it is affected by disturbances over the TP were analyzed from 1981 to 2015, a period of 35 years. The Baiu season over Kyushu is defined as the period between May 31 and July 19, which includes the climatological Baiu season in both northern and southern Kyushu, as defined by

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the Japan Meteorological Agency (JMA). An interannual variation in the Baiu season is not considered in this study.

To detect heavy precipitation days over Kyushu, two kinds of dataset were used: the Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of water resources project (APHRODITE and APHRODITE2; Kamiguchi et al. 2010, Hamada et al. 2011, Yatagai et al. 2012), version V1207 with a 0.05° × 0.05° resolution covering Japan, and a typhoon track dataset provided by JMA. The daily precipitation of APHRODITE/APHRODITE2 was averaged over Kyushu (land area in 30°N−35°N, 127.5°E−132.5°E; solid black rectangle in Fig. 1a), and days with daily precipitation larger than 1.0 mm was defined as precipitation days. In the precipitation days, days that ranked in the top 10% of the area-averaged daily precipitation were classified as heavy precipitation days. The four days when a typhoon was present over 27°N−38°N, 124.5°E−135.5°E (dashed black rectangle in Fig. 1a) were removed from the heavy precipitation days to exclude direct effects of the typhoon on heavy precipitation. As a result, 109 cases of heavy precipitation days were detected. Heavy precipitation days are designated d = 0 in this study; the days that occur one, two, three, four, five, six, and seven days before the heavy precipitation occurrence are designated d = −1, −2, −3, −4, −5, −6, and −7, respectively.

To investigate the characteristics of synoptic-scale atmospheric conditions on heavy precipitation days (d = 0) and several prior days (d = −1, −2, −3, −4, −5, −6, and −7), a composite analysis was conducted for precipitation, relative vorticity, vertical integrated water vapor flux, daily-mean outgoing longwave radiation (OLR), potential temperature, and potential vorticity (PV). The anomalies were also calculated for several variables as the difference between heavy precipitation days and climatological values, and the climatological atmospheric conditions were calculated for May 31 to July 19 during 1981−2015. For each anomaly, the one sample *t*-test was used to calculate the statistical significance at the 85%, 90%, and 95 % confidence levels. This analysis employed the APHRODITE/APHRODITE2 versions V1101/V1101EX with 0.25° × 0.25° resolution covering the Asian monsoon region (Yatagai et al. 2012), the Japanese 55-year reanalysis with 1.25° × 1.25° resolution (JRA-55; Kobayashi et al. 2015; Harada et al. 2016), and the NOAA Interpolated OLR with 2.5° × 2.5° resolution (Liebmann and Smith 1996). Note that the analyzed time of JRA-55 was 06 Z to clearly show the surface heating over the TP discussed in Section 3.3.

3. Results

3.1 Characteristics of heavy precipitation over Kyushu

Figure 1a shows the spatial distribution of climatological precipitation over Japan. During the analysis period, precipitation is generally observed over Kyushu and coastal regions of southwestern Japan as well as central Japan. Precipitation exceeds 12 mm day^{-1} over most of Kyushu. However, on heavy precipitation days (Fig. 1b), precipitation exceeding 100 mm day^{-1} occurs only over Kyushu and is equivalent to 400%−600% of the climatological mean precipitation. As a result, a dry–wet gradient from north to south is emphasized in Japan during heavy precipitation days, relative to the climatological average.

3.2 Synoptic-scale atmospheric conditions causing heavy precipitation over Kyushu

Before describing the analysis of synoptic-scale atmospheric conditions on heavy precipitation days, their climatological characteristics are outlined. The climatological averages of relative vorticity at 700 hPa are negative south of Japan and are associated with the development of the NPSH. The values are positive over Japan and the surrounding region except for parts of central and northern Japan (Fig. 2a). The anticyclonic circulation of the NPSH brings large amount of water vapor from subtropical regions to the southeastern part of China and the southern part of Japan, which forms the climatological cloud bands of the Baiu/Meiyu (Fig. 2b). A pair of positive and negative relative vorticities appears over and to the east of the Bay of Bengal (BoB), which enhances moisture transport from the BoB to the north and northeast. Active cloud convection occurs over the BoB, Bangladesh, the northern part of Southeast Asia, and the eastern TP.

A comparison with climatological synoptic-scale atmospheric conditions reveals that the positive–negative gradient of relative vorticity is stronger at 700 hPa between northwest and southeast Kyushu on heavy precipitation days (i.e., d = 0), resulting in enhanced moisture flow from the northwestern Pacific to Kyushu (Figs. 2c and 2d). Heavier precipitation is observed only over Kyushu, as mentioned above, and a decrease in OLR is also found over Japan. An anomalous anticyclonic circulation associated with NPSH development is consistent with the suppression of cloud convection over the ocean south of Kyushu, which may form in association with active cloud convection over Kyushu.

The time evolution of the northwest–southeast gradient of relative vorticity anomalies over Kyushu was examined. A small area with positive anomalies of relative vorticity at 700 hPa appears over the Sichuan Basin (around 31°N, 105°E) three days before the occurrence of heavy precipitation (i.e., d = −3; compare Figs. 3a, 3b, and 3c). The cyclonic circulation anomalies rapidly extend to the east (d = −2; Fig. 3d) and are enhanced over the eastern China and its east (d = −1; Fig. 3e). After that, the center of anomalous cyclonic vorticity moves to the northwest of Kyushu on the heavy precipitation day (d = 0; Fig. 2c). An area with high precipitation also propagates from central China to Kyushu, and is associated with a cyclonic vorticity anomaly. A negative relative vorticity anomaly at 700 hPa exists south of Kyushu for at least seven days before the onset of heavy precipitation (Fig. 3). This anomalous anticyclonic vorticity develops and moves northwestward on d = −1 and d = 0, which also contributes to enhancement of the northwest–southeast gradient of the relative vorticity anomaly.

The eastward propagation of the positive anomaly of relative vorticity corresponds to that of the negative OLR anomaly (i.e., the active cloud convection anomaly). Compared with the climatological values, the southwesterly moisture flow and cloud convection along the northwestern edge of the NPSH are slightly intensified at least seven days before the onset of heavy precipitation (not shown). Under these conditions, anomalous cloud convection is observed over the northeastern TP on d = −4 (compare Figs. 4a and 4b), which moves to central–eastern China (around 31°N, 110°E) the next day (Fig. 4c). This negative OLR anomaly couples with that along the northwestern edge of the NPSH and is enhanced during d = −2 and −1 (Figs. 4d and 4e). This time evolution of cloud convection is more clearly shown in a figure for the anomalies of OLR and the vertical integrated moisture flux averaged over 30°N−35°N (Fig. 5).

Thus, the abundant moisture inflow to Kyushu on heavy precipitation days is mainly caused by the intensification of the relative vorticity gradient around Kyushu. This evident is consistent with Ohba et al. (2015) and Nguyen-Le et al. (2017). The eastward propagation of a cyclonic vorticity anomaly from China is important for the formation of the relative vorticity gradient, as well as the development of the NPSH.

3.3 Relationship between cyclonic circulation generated over the TP and heavy precipitation over Kyushu

As described in Section 1, during summer, the plateau-scale disturbance accompanied by the cloud convection is generated over the TP because of strong surface heating, water vapor inflow, and moisture supplied from the ground (Tao and Ding, 1981; Wang 1987; Sugimoto and Ueno 2010). This system sometimes propagates to the east and enhances precipitation along the Yangtze River (Yasunari and Miwa 2006; Li et al. 2008; Feng et al. 2014). Figure 3c shows that a positive anomaly of relative vorticity appears at 700 hPa over the Sichuan Basin three days before the onset of heavy precipitation over Kyushu. This vorticity anomaly may be related to the cyclonic circulation generated over the TP, although it is not evident at 700 hPa because the altitude of the TP is ~4000 m. To confirm this hypothesis, vertical–longitudinal cross-sections of the PV and the anomaly in potential temperature

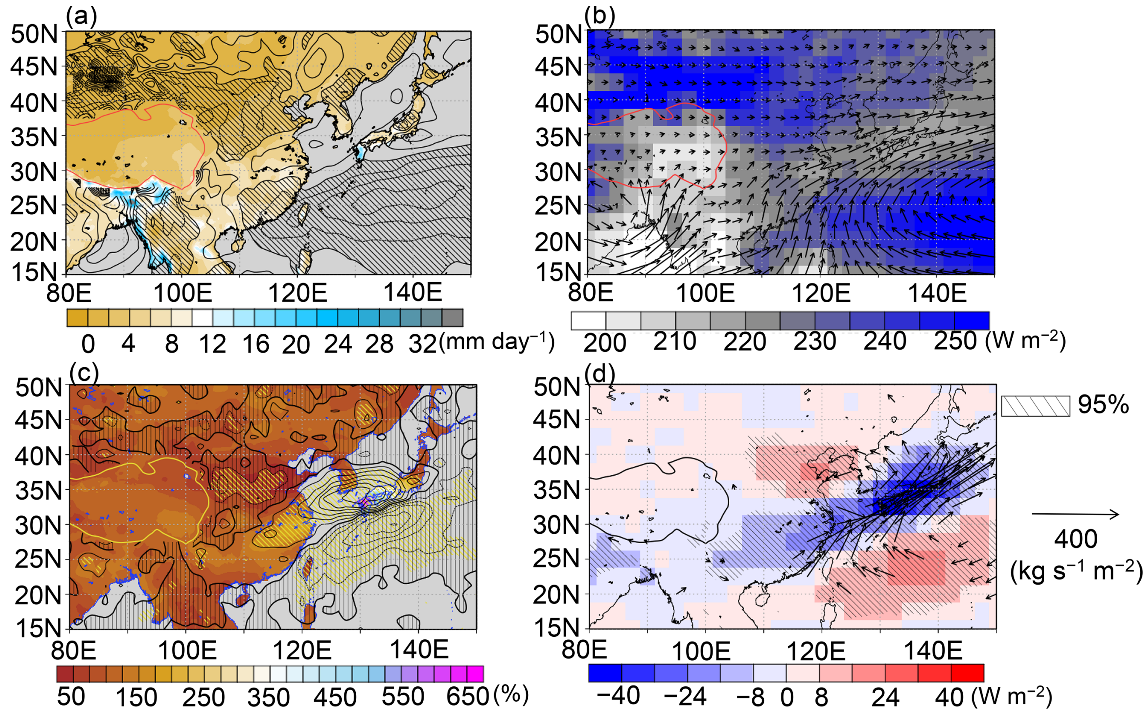


Fig. 2. Spatial distribution of climatological (a) precipitation over land (shading) and relative vorticity (contours; 0.5×10^{-5} s^{-1} intervals) and (b) OLR (shading) and vertical integrated water vapor flux (vector). (c) As in (a) but for the change ratio of composite precipitation on heavy precipitation days compared with climatological averages (shading) and anomalies of relative vorticity (contours; 0.5×10^{-5} s^{-1} intervals), calculated as the composite of heavy precipitation day minus climatological average. (d) As in (c) but for anomalies of OLR (shading) and vertical integrated water vapor flux (vector). In (a) and (c), the black hatching for relative vorticity indicates the area with negative values and negative anomalies. The yellow and black hatchings in (c) and (d) indicates statistical significance at the 95% confidence levels, respectively. The vectors in (d) are drawn over the grids with statistical significance at the 95% confidence levels either U or V component of vertically integrated water vapor flux. Gray shading in (a) and (c) indicates areas with no precipitation data. Red solid lines in (a) and (b), a yellow solid line in (c), and a black thick solid line in (d) indicate an altitude of 3000 m.

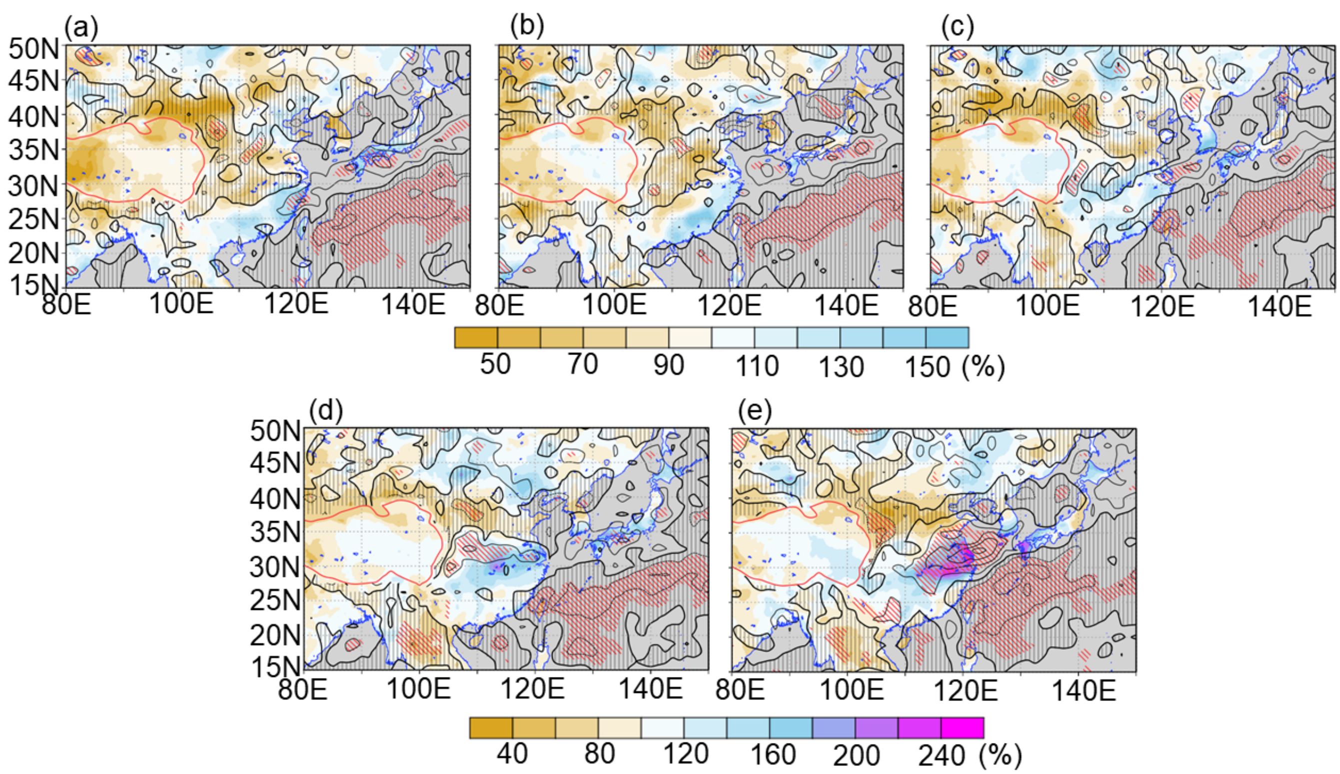


Fig. 3. As in Fig. 2c but for (a) d = −5, (b) d = −4, (c) d = −3, (d) d = −2, and (e) d = −1 with different shading intervals. The red hatching indicates statistical significance at the 95% confidence levels. A red solid line indicates an altitude of 3000 m.

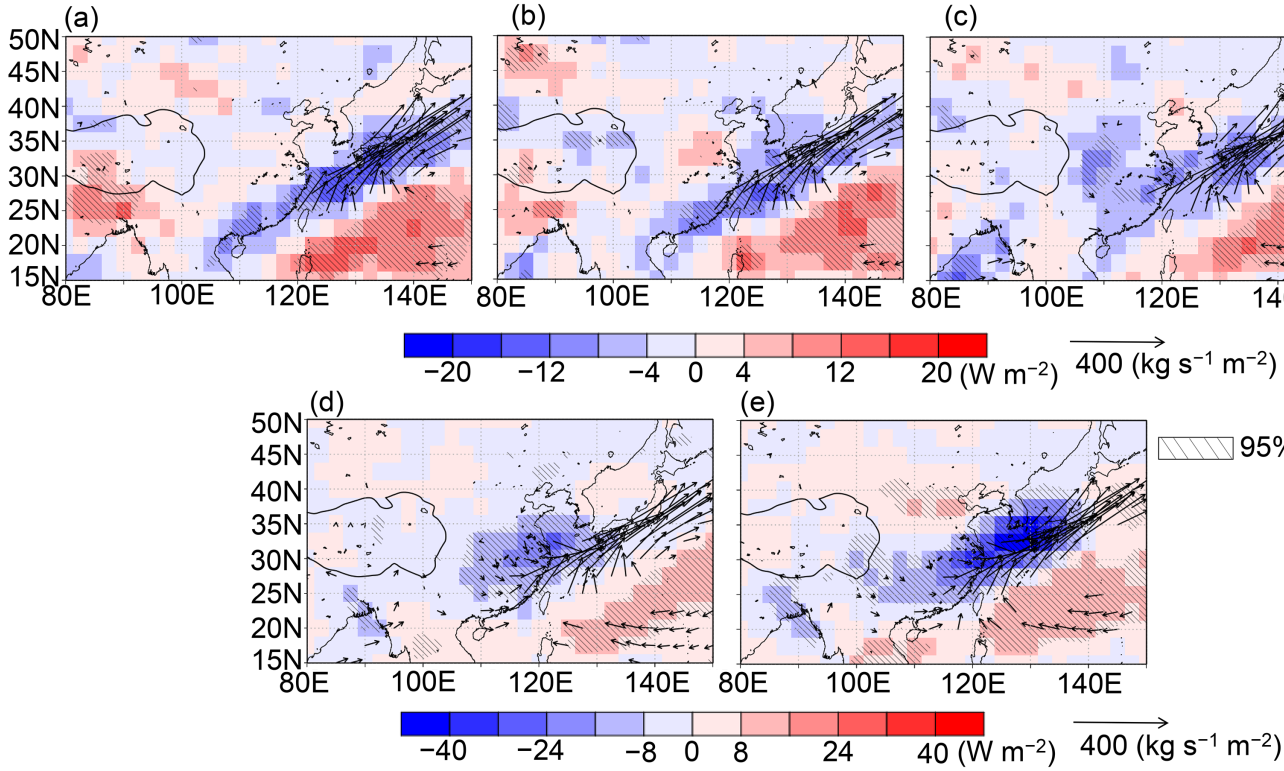


Fig. 4. As in Fig. 2d but for (a) d = −5, (b) d = −4, (c) d = −3, (d) d = −2, and (e) d = −1 with different shading intervals.

are shown in Fig 6.

A shallow warm anomaly of potential temperature with near-surface high PV is found below 500 hPa level over the TP on d = −5, suggesting the occurrence of plateau-scale disturbance associated with surface heating over the TP (Fig. 6a), although high PV without any significant surface heating is analyzed d = −7 and −6 (Fig. S1). The active cloud convection is evident over the northeastern TP on the next day (d = −4, Fig. 4b), which is consistent with a formation of the meso-scale convective system over the eastern TP on the following day of the thermal low generation, as described by Sugimoto and Ueno (2010). Indeed, the warmer layer reaches 300 hPa level over the eastern TP on d = −4 (Fig. 6b), implying the latent heating from the cloud, although the warming is not statistically significant except below 500 hPa level. The area with high PV expands up to 400 hPa and toward eastern slopes of TP on d = −3 (Fig. 6c), which has already shown as the appearance of positive anomaly of relative vorticity at 700 hPa over the Sichuan Basin (Fig. 3c), and then, the high PV in the mid-troposphere (600−400 hPa) extends to the outside of TP on d = −2 (Fig. 6d). During d = −3 and −2, the troposphere is gradually warmed particularly over 95°E−125°E since the cloud convection gets more and more active over the central and eastern China (Figs. 4c and 4d). The cloud convection with latent heating and the mid-troposphere disturbance are likely to influence each other. The high PV area in the mid-troposphere over 115°E−130°E couples with the upper-level high PV on d = −1 (Fig. 6e), and the heating between mid- and upper troposphere enhances at the slightly east of the coupled high PV. The high PV area moves to east in the mid-troposphere and extends to the lower troposphere on d = 0 with the mid- and upper troposphere heating over 120°E−145°E (Fig. 6f). At this time, the eastern boundary of high PV in the lower and mid-troposphere is approximately 130°E, which is just above the area with abundant moisture inflow and heavy precipitation occurrence over Kyushu.

These temporal changes in PV and potential temperature anomaly suggest that the disturbance approaching to northwest of Kyushu on the heavy precipitation day is 1) generated in near-surface layer over the TP (including slopes) associated with surface heating and 2) maintained by the eastward propagation of the coupled system between the cloud convection and the plateau-scale disturbance. The upper-level PV may also contribute to the maintenance of disturbance. The influences of the latent heating and the upper-level PV on a development of Baiu frontal depression have been already shown by several studies (Akiyama 1984; Chang et al. 1998; Shibagaki and Ninomiya 2005; Tochimoto and Kawano 2012; Tochimoto and Kawano 2017). The result of this study is consistent with them and additionally proposes an impact of the plateau-scale disturbance with cloud convection on the occurrence of abundant moisture inflow and heavy precipitation over Kyushu.

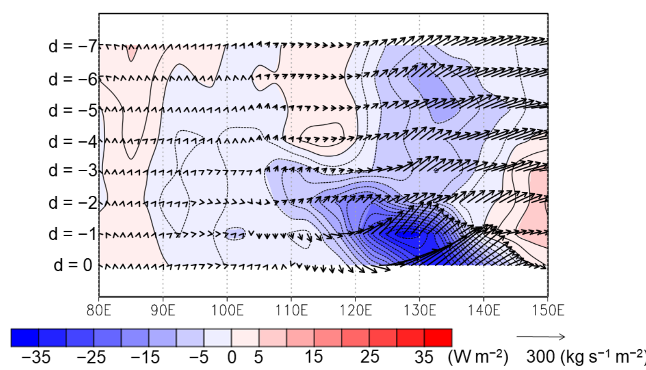
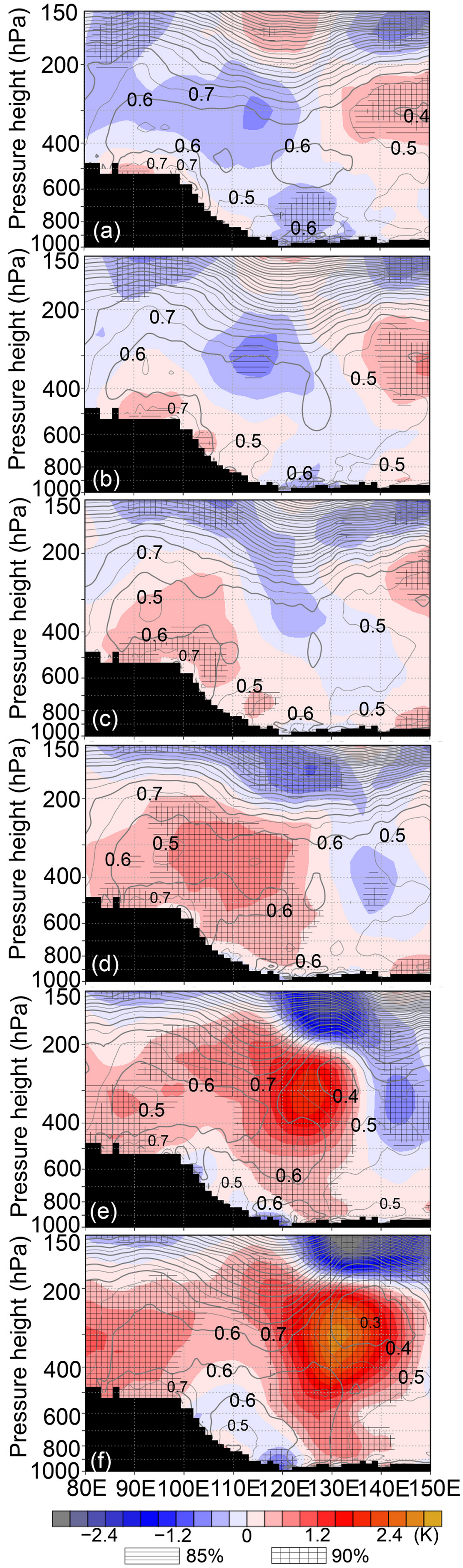


Fig. 5. Area-averaged anomalies of OLR (shading with 5.0 W m^{-2} intervals and contours with 2.5 W m^{-2} intervals) and vertical integrated water vapor flux over 30°N−35°N, calculated as the composite of heavy precipitation day minus the climatological average, from d = −7 to d = 0.



4. Conclusions and discussions

The synoptic-scale atmospheric conditions before and on days of heavy precipitation over Kyushu during the Baiu season have been investigated statistically. Based on a composite analysis, heavy precipitation and active cloud convection occur over Kyushu along the Baiu rain band when a cyclonic vorticity anomaly approaches from China to the northwest of Kyushu over several days. The enhancement of a positive–negative gradient of relative vorticity over Kyushu causes active moisture flow into western Japan, which effectively intensifies Baiu activity and precipitation over Kyushu. The disturbance propagating from the west is coupled with active cloud convection, and initially occurs over the TP in association with surface heating. It is concluded that the eastward propagation of this plateau-scale disturbance with the cloud convection is a driver of abundant moisture transport and heavy precipitation over Kyushu. This study could not identify how large the impact of the latent heating from the cloud and the upper-level PV on the disturbance development and/or maintenance. Sensitivity experiments using an atmospheric model as performed by Tochimoto and Kawano (2017) would be required to reveal this issue.

Sampe and Xie (2010) and Kosaka et al. (2011) proposed an important role for warm temperature advection from the TP to the east in the enhancement of cloud convection along the Baiu. The horizontal warm advection at 500 hPa is also analyzed in this study (not shown). Although a climatological horizontal advection of warm air is confirmed from the TP to the east, its intensification is not evident when heavy precipitation occurs over Kyushu.

As shown in Figs. S2a and S2b, the seasonal occurrence frequency of heavy precipitation days is almost constant from mid-June to mid-July, and its interannual variation is large. This may be associated with annual variations in the occurrence of plateau-scale disturbances. Thus, the linkage between TP monsoon activity and heavy precipitation over Japan should be investigated in a future study.

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Fig. 6. Vertical–longitudinal cross-sections of potential vorticity (gray contours; 0.1 PVU intervals, 1 PVU = 10^{-6} m^2 s^{-1} K kg^{-1}) and anomaly of potential temperature (shading) averaged over 30°N−35°N, calculated as the composite of heavy precipitation day minus climatological average on (a) d = −5, (b) d = −4, (c) d = −3, (d) d = −2, (e) d = −1, and (f) d = 0. The thick gray lines are 0.2 PVU intervals. The black hatchings indicate statistical significance at the 85% and 90% confidence levels, respectively. Black shading indicates the topography.

Supplements

Supplementary Figure 1 (Fig. S1) is as in Fig. 6 but for (a) d = −7 and (b) d = −6. Supplementary Figure 2 (Fig. S2) shows the occurrence frequency of heavy precipitation days, (a) seasonal variations and (b) annual variations.

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