Precipitation Enhancement via the Interplay between Atmospheric Rivers and Cutoff Lows

HIROKI TSUJI AND YUKARI N. TAKAYABU

Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan

(Manuscript received 5 October 2018, in final form 19 April 2019)

ABSTRACT

A significant enhancement of precipitation can result from the interplay between two independent, large-scale phenomena: an atmospheric river (AR) and a cutoff low. An AR is a long, narrow region with a deep moist layer. A cutoff low is an upper-level cyclonic eddy isolated from the meandering upper-level westerly jet. Herein, we construct composites of cutoff lows both close to an AR (AR-close category) and distant from an AR (AR-distant category) over a 14-yr period across the western North Pacific region. A comparison between the two categories shows an enhanced precipitation area to the northwest of the cutoff low and to the south of the AR axis in the AR-close category. The horizontal formation among the AR, cutoff low, and enhanced precipitation area in the composite coincides with that in a disastrous flood event that occurred in Hiroshima, Japan, in 2014. The deep moist layer associated with the AR, and the destabilization and isentropic up-gliding effect associated with the cutoff low are also observed in both the composite and the Hiroshima cases. We further evaluate the distribution of quasigeostrophic forcing ($\mathbf{Q}$ vector) for vertical motion. This shows that warm air advection associated with the AR overcomes the descending forcing inherent in the northwest of the cutoff low and makes the instability and up-gliding effect in that region more effective. These results indicate that the interplay between ARs and cutoff lows is a common mechanism in the enhancement of precipitation and the Hiroshima case is an extreme precipitation event caused by this interplay.

1. Introduction

A disastrous flood occurred in Hiroshima, Japan, on 19 August 2014, with more than 200 mm of cumulative rainfall recorded over a 3-h period. [Hirota et al. \(2016, hereafter H16\)](#) analyzed this flood event and determined that two large-scale atmospheric features, an atmospheric river (AR) and a cutoff low, played a significant causal role in this torrential rainfall.

ARs are long, narrow regions with high water vapor content that contribute to a large portion of water vapor transport from the tropics to the midlatitudes ([Zhu and Newell 1998](#); [Ralph et al. 2004](#); [Gimeno et al. 2014](#)). They are identified more frequently in midlatitude ocean basins than over land or at other latitudes ([Guan and Waliser 2015](#)). ARs possess large water vapor content in both the boundary layer and the free troposphere

([Ralph et al. 2004](#)). Heavy rainfall events along the western margins of continents generally occur in conjunction with the landfall of ARs ([Ralph et al. 2006](#); [Dettinger et al. 2011](#)), and most of the precipitation associated with ARs occurs as orographic precipitation ([Ralph et al. 2011](#)). A large fraction of ARs occur during the cool season because they are associated with the warm sector of extratropical cyclones ([Gimeno et al. 2014](#)). However, in the western North Pacific, the highest frequency of ARs is observed during the summer months, associated with the East Asia monsoon, and such ARs are noted to have complex shapes ([Mundhenk et al. 2016](#); [Kamae et al. 2017](#)).

Cutoff lows are cold-core upper cyclonic eddies that are isolated from the meandering, upper-level westerly jet. An approaching cutoff low destabilizes the atmosphere due to the accompanying upper-level cold air and induces severe weather events such as hailstorms ([Chen and Tang 2004](#); [Zhang et al. 2008](#)).

Cutoff lows over the western North Pacific are generated around a mid-Pacific trough located at 160°E–160°W ([Sakamoto and Takahashi 2005](#); [Wen et al. 2018](#))

Denotes content that is immediately available upon publication as open access.

Corresponding author: Hiroki Tsuji, h-tsuji@aori.u-tokyo.ac.jp

FIG. 1. Synoptic patterns on or before the day when the Hiroshima rainfall event occurred. Color shows the potential vorticity on the 350-K isentropic surface (PVU). Red contours show precipitable water anomalies (mm, only for ≥ 10 mm). Vectors show wind on the 200-hPa pressure surface (m s^{-1} , only for $\geq 30 \text{ m s}^{-1}$). The time is 1800 UTC in all the figures.

and are linked to Rossby wave breaking (Wernli and Sprenger 2007). An anticyclone generally occurs below a cutoff low (Sugi and Kanamitsu 1982; Chen and Tang 2004; Nieto et al. 2008). Cutoff lows have a greater effect on precipitation patterns over dry regions than over wet regions (Favre et al. 2013; Abatzoglou 2016).

The H16 study investigated the effects of a cutoff low and an AR on precipitation through potential vorticity (PV) inversion analyses and sensitivity studies using a cloud-resolving model. H16 emphasized the essential role of interplay between an AR, existing along with a large-scale trough and providing anomalous moisture to the free troposphere, and an upper tropospheric cutoff low, which dynamically induced upward motion in the midtroposphere as well as thermodynamically destabilized the atmosphere in the midlevels, around 600 hPa. The main purpose of this study is the statistical investigation of the enhancement of precipitation through the interplay between an AR and a cutoff low, as in the case of the extreme rainfall at Hiroshima.

To demonstrate synoptic environments for precipitation enhancement through this interplay, the synoptic

environments of the Hiroshima case are shown in Fig. 1. The cutoff low related to the Hiroshima case was generated at around 160°E – 180° , around the mid-Pacific trough (Fig. 1a). It traveled westward over the western North Pacific (Figs. 1b,c), before moving northward toward the large-scale trough located over China (Figs. 1c,d). The corresponding AR remained stationary along with an upper westerly jet (e.g., Horinouchi 2014). The Hiroshima case occurred when the cutoff low approached and intersected the AR (Fig. 1d).

A number of studies concerning precipitation enhancement related to upper tropospheric phenomena have been performed for localities in Europe and the United States. For example, Martius et al. (2006) showed that an upper tropospheric PV streamer was situated over western Europe in 73% of days when the Swiss Alpine south side was characterized by extreme precipitation. Studies by Massacand et al. (1998), Froidevaux and Martius (2016), and Giannakaki and Martius (2016) have also noted the importance of upper tropospheric phenomena on extreme precipitation along the Swiss Alpine south side. Hardy et al. (2017) investigated the sensitivity of

accumulated precipitation across the United Kingdom to upper-level PV anomalies. Oakley and Redmond (2014) and Abatzoglou (2016) documented the contribution of cutoff lows to precipitation in the United States. In other regions, Knippertz and Martin (2005) demonstrated the importance of moisture transport in the mid-to upper troposphere, together with upper tropospheric dynamics, to produce intense precipitation in subtropical and tropical West Africa. de Vries et al. (2018) also showed the importance of an interaction between an upper tropospheric PV streamer and integrated water vapor transport for extreme precipitation events in the Middle East. In relatively humid regions such as East Asia, the characteristics of the lower troposphere, such as moisture convergence in the boundary layer, a low-level jet, and topographic effects, are usually considered the primary factors for heavy rainfall events (Chen et al. 2005; Kato 2006; Juneng et al. 2007; Moore et al. 2012; Tsuguti and Kato 2014; Tu et al. 2014). The mechanism that caused the 2014 Hiroshima precipitation event is still debated.

The objective of this study is to determine whether the interplay between cutoff lows and ARs, such as that occurring in the Hiroshima case, typically induces precipitation enhancement. We evaluate this by statistically investigating the impact of this interplay on precipitation enhancement. We begin by describing the data used in the analyses (section 2) and then provide an overview of the implemented methods to produce anomaly data, detect ARs and cutoff lows, produce composites, and evaluate quasigeostrophic (QG) forcing for vertical motions (section 3). We present the results of our statistical analyses in section 4 and conclude with a discussion of the effects of the interplay on precipitation in section 5.

2. Data used in the analysis

The Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015; Harada et al. 2016), which provides global 6-hourly atmospheric variables at a $1.25^\circ \times 1.25^\circ$ spatial resolution, is used to detect cutoff lows and ARs. The data are also used to analyze environmental characteristics such as temperature, specific humidity, PV, and vertical velocity and evaluate QG forcing. The precipitation dataset is obtained from the Global Satellite Mapping of Precipitation (GSMaP) reanalysis product (ver. 6) from the Global Precipitation Measurement (GPM) mission (Kubota et al. 2007; Aonashi et al. 2009), which provides hourly precipitation at a $0.1^\circ \times 0.1^\circ$ spatial resolution between 60°N and 60°S . The precipitation data are converted to 6-hourly data *via* time averaging. We used the best track data provided

TABLE 1. Monthly number of cutoff lows grouped into either the AR-close category or the AR-distant category. Parentheses indicate cases not used in the analyses.

	AR-close category	AR-distant category
Jan	(0)	(0)
Feb	(0)	(0)
Mar	(1)	(0)
Apr	(1)	(2)
May	12	9
Jun	13	16
Jul	21	20
Aug	36	31
Sep	36	32
Oct	18	11
Nov	(3)	(3)
Dec	(3)	(1)

by the Joint Typhoon Warning Center (JTWC) to obtain information on the locations of tropical cyclones, which is used in cutoff low detection and AR detection to eliminate cutoff lows and ARs located near tropical cyclones.

May to October 2000–13 was chosen as the period of analysis because almost all cutoff lows occur during these months (see Table 1). The period from 2000 to 2013 is set due to the limited period of the GSMaP reanalysis product. The analysis region spans 0° – 60°N , 100° – 200°E (160°W).

3. Method

a. Anomaly data

Anomalies from a 31-day running mean daily climatology for 1986–2015 at each JRA-55 grid are used as precipitable water anomalies to detect ARs. The 31-day running mean daily climatology is the average of precipitable water for 31 days centered on each day for 30 yr at each grid. Anomaly data for the specific humidity and temperature of the analyses are calculated by the same method.

b. Cutoff low detection

A cutoff low is defined as a region surrounded by a 2-PVU ($1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m}^2 \text{ s}^{-1}$) contour on an isentropic surface and appears as an isolated stratospheric PV (Hoskins et al. 1985; Nieto et al. 2008). We use PV on the 350-K isentropic surface to detect cutoff lows traveling over the western North Pacific. The following criteria are used for the detection of cutoff lows: 1) the region is surrounded by a 2-PVU contour, 2) the maximum PV value is larger than 3 PVU, 3) the region is not directly adjacent to the boundary of the analysis region, 4) the maximum PV positions are separated by $\leq 5^\circ$ between two continuous

JRA-55 time steps (6 h), 5) the distance between the centers of any tropical cyclones and the region is $>5^\circ$, and 6) these criteria are satisfied for more than 48 h.

c. AR detection

ARs are defined using the vertically integrated precipitable water anomaly with the following conditions: 1) the region is surrounded by a 10-mm contour of the anomaly, 2) the maximum value of the anomaly is >15 mm, 3) the distance between the centers of any tropical cyclones and the region is $>5^\circ$, 4) the centroid of the anomaly in the region is located north of 20°N , 5) the length of the AR axis is longer than 2000 km, and 6) the length/width ratio of the AR is >2 , where the axis length and width of the AR are calculated following the method of Guan and Waliser (2015). Thresholds of 10 and 15 mm of precipitable water anomalies correspond to around $\bar{x} + 1.3\sigma_x$ and $\bar{x} + 2\sigma_x$, respectively, in an area in which an AR has been detected ($20^\circ\text{--}60^\circ\text{N}$, $100^\circ\text{--}200^\circ\text{E}$), where $\bar{x}$ and σ_x indicate an averaged precipitable water anomaly (0.26 mm) and its standard deviation (7.51), respectively, during the analysis period.

Our method for detecting ARs using the precipitable water anomaly is distinct from methods implemented in previous AR studies (e.g., Zhu and Newell 1998; Ralph et al. 2004; Dettinger et al. 2011). We adopt the anomaly based method because the ARs in the western North Pacific region occur in a moisture-rich environment (Guan and Waliser 2015) due to the transport of large amounts of water vapor from the tropics, particularly during the summer season, associated with the baiu front and summer monsoon (Knippertz and Wernli 2010). Previous studies have also used integrated water vapor transport anomalies to detect ARs in the western North Pacific region (e.g., Mundhenk et al. 2016; Kamae et al. 2017).

d. Definition of the AR-close and AR-distant categories and composite method

Cutoff lows detected using the aforementioned criteria can be further grouped into two categories, AR-close and AR-distant, based on the smallest distance between the axis of an AR and a cutoff low center. We assume that the interplay enhances precipitation around AR-close category cutoff lows such as in the Hiroshima case. In contrast, we assume that cutoff lows in the AR-distant category have little interplay with the AR. The cutoff low center is defined as the maximum value of a horizontally smoothed PV inside a closed 2-PVU contour at each time step. The smoothing of PV for each grid is performed by calculating the averages of PV at the grid itself and at the eight grids surrounding it. A cutoff low

is grouped into the AR-close category when the smallest distance between the axis of an AR and a cutoff low center is between 5° and 12.5° for more than two continuous JRA-55 time steps at any point during its life cycle. In contrast, a cutoff low is grouped into the AR-distant category when the smallest distance is between 12.5° and 20° . We exclude cutoff lows with distances smaller than 5° . Such cases are not appropriate for the analysis of interplay since ARs probably penetrate into cutoff lows which generally possess horizontal scales of $3^\circ\text{--}5^\circ$ (Wen et al. 2018).

The AR-close and AR-distant categories contain 136 and 119 cutoff low cases, respectively, where “a case” is defined as the average of all snapshots that satisfy the criteria. The total numbers of snapshots satisfying the AR-close and AR-distant criteria are 1009 and 781, respectively. The average is calculated by aligning the cutoff low center. Composite analyses can then be performed in a manner similar to the average method for “a case,” with the cases in each category considered in the analyses.

We perform an additional analysis involving subdivision of the AR-close category into three classes (section 4d). The distance criteria for the three classes are set to $5^\circ\text{--}7.5^\circ$ (named the $5^\circ\text{--}7.5^\circ$ class), $7.5^\circ\text{--}10^\circ$ (named the $7.5^\circ\text{--}10^\circ$ class), and $10^\circ\text{--}12.5^\circ$ (named the $10^\circ\text{--}12.5^\circ$ class). The numbers of cutoff low cases in each class are 54, 69, and 85, respectively. The distance criterion for the AR-distant category is set to $15^\circ\text{--}17.5^\circ$ to adjust the range of the distance criterion, and the number of cutoff low cases in this category is 48.

e. Statistical testing method

Statistical significance is determined *via* the bootstrap method. At each grid point, N samples are randomly chosen from N cases with replacement and averaged, where N indicates the number of cases in each category. This process is repeated 2000 times, and the statistical significance of the results is determined from these 2000 averages.

f. Method to evaluate QG forcing for vertical motion

We use the **Q**-vector form of the QG omega equation (Hoskins et al. 1978) to evaluate the distribution of large-scale dynamic forcing for vertical motion. Following Holton (2004, p. 170), the **Q**-vector form of the omega equation is defined as

$$\sigma \nabla^2 \omega + f_0^2 \frac{\partial^2 \omega}{\partial p^2} = -2 \nabla \cdot \mathbf{Q} + f_0 \beta \frac{\partial v_g}{\partial p} - \frac{\kappa}{p} \nabla^2 J, \quad (1)$$

where

FIG. 2. Geographical distributions of cutoff lows in the (a) AR-close and (b) AR-distant categories. Each dot shows the location of the center of a case-averaged cutoff low. Black contours indicate the time-averaged potential vorticity on the 350-K isentropic surface (unit: PVU) during the analysis period. Color shows the time-averaged AR frequency (unit: %) during the analysis period. Blue rectangles indicate the location of the mid-Pacific trough.

$$\mathbf{Q} = \left(-\frac{R}{p} \frac{\partial \mathbf{V}_g}{\partial x} \cdot \nabla T, -\frac{R}{p} \frac{\partial \mathbf{V}_g}{\partial y} \cdot \nabla T \right), \quad (2)$$

and σ is a standard atmosphere static stability parameter, ω is the vertical velocity, f_0 is the Coriolis parameter, R is the gas constant, p is pressure, $\mathbf{V}_g = (u_g, v_g)$ is a geostrophic wind vector, x is an eastward distance, y is a northward distance, β is the variation in the Coriolis parameter with latitude, κ is the ratio of the gas constant to the specific heat at constant pressure, J is the adiabatic heating rate, and T is temperature. Note that we focus on the QG forcing term ($-2\nabla \cdot \mathbf{Q}$) in this analysis. A positive value of the QG forcing term ($-2\nabla \cdot \mathbf{Q} > 0$) indicates QG ascending motion. We calculate $\mathbf{Q}$ -vector divergence using JRA-55 data after smoothing the horizontal resolution to a 2.5° grid.

4. Results

a. Comparison of cutoff lows with and without ARs

Almost all cutoff lows in this analysis occurred between May and October, with only a few cases observed between November and April (Table 1). This seasonal dependence is consistent with the climatology of cutoff lows in previous studies (Chen and Chou 1994; Wernli and Sprenger 2007; Wen et al. 2018). Considering this seasonal dependence of cutoff lows, the following analyses are performed for 6 months from May to October over 14 yr.

The geographical distributions of cutoff lows in the AR-close and AR-distant categories are shown in Fig. 2. The cutoff lows are located in the region of the

mid-Pacific trough (the region surrounded by a blue rectangle in Fig. 2) and its west. The average moving directions of cutoff lows in both categories are west to northwest (not shown). These results are consistent with the reported characteristics of cutoff lows over the western North Pacific (Kelley and Mock 1982; Chen and Chou 1994; Wen et al. 2018) and the Hiroshima case (Fig. 1). In total, 54% of AR-close-category cutoff lows are located to the north of 25°N , whereas 30% of AR-distant-category cutoff lows are located to the north of 25°N . Because ARs are frequently located to the north of 25°N (Fig. 2), this result indicates that cutoff lows have a high probability of approaching ARs when they approach the upper westerly jet in the final stage of their life cycle (cf. Nieto et al. 2008).

Figure 3 illustrates the monthly mean AR frequency, 200-hPa wind vectors, and PV on 350-K isentropic surfaces between 2000 and 2013. Although the AR locations shift month by month, ARs are located to the south of an upper westerly jet in all the months, consistent with the findings of Horinouchi (2014).

Figure 4 shows composites of precipitation, precipitable water anomalies, and PV for the AR-close and AR-distant cutoff lows. A large amount of precipitation occurs to the south of the cutoff low (south of the -5° relative latitude [Rlat]) in both categories. These high precipitation rates result from tropical convection and are less obvious when climatological values of precipitation are subtracted (not shown). In the southeast of the cutoff low, areas with high precipitation rates extend northward. Enhanced precipitation to the southeast of the cutoff low is consistent with the findings of previous

FIG. 3. Monthly mean AR frequency in the western North Pacific region (color, %), potential vorticity on the 350-K isentropic surface (contour, only for 1, 2, and 4 PVU), and 200-hPa wind vectors (m s^{-1} , only for $\geq 20 \text{ m s}^{-1}$). Averages are calculated for the time period between 2000 and 2013.

studies (Sadler 1976; Shimamura 1981, 1982; Kelley and Mock 1982; Chen and Chou 1994; Knippertz and Martin 2007; Nieto et al. 2008). Hereafter, this area is referred to as the cutoff-southeast (SE)-rain area.

Another area of enhanced precipitation can be confirmed at the north of a composite AR axis (the ridge of a composite precipitable water anomaly) along an upper tropospheric trough to the north of the cutoff low. Hereafter, this area is referred to as the AR-rain area. The enhanced precipitation area to the north of the AR axis is consistent with a northward tilt of dynamical forcing by the upper tropospheric trough (Horinouchi 2014; Yokoyama et al. 2017). Figure 4 of Horinouchi (2014) is particularly useful in confirming that the precipitation maximum is found to the north of the specific humidity maximum.

In the AR-close category, another enhanced precipitation area is observed to the northwest of the cutoff low and to the south of the AR axis in the AR-close category. Hereafter, this area is referred to as the cutoff-northwest (NW)-rain area. Enhanced precipitation to the northwest of the cutoff low in the AR-distant

category is not identified. Therefore, enhanced precipitation in the cutoff-NW-rain area is likely associated with the interplay between the AR and the cutoff low.

b. Comparison with the Hiroshima case

1) HORIZONTAL STRUCTURES

The difference between the precipitation composites of the AR-close and AR-distant categories is depicted in Fig. 5a and illustrates the effect of the coexistence of an AR and a cutoff low. Significant differences in precipitation are observed for both the AR-rain area and the cutoff-NW-rain area. Figure 5b illustrates the precipitation, 350-K PV, and precipitable water anomaly during the 2014 Hiroshima precipitation event. Comparing the composite (Fig. 5a) with the Hiroshima case (Fig. 5b), a very similar relationship is identified in the horizontal formation of the AR, the cutoff low, and the enhanced precipitation area. The location of a significant difference area relative to the cutoff low center in the cutoff-NW-rain area of the composite is found to coincide with the location of the intense rainfall event relative to the

FIG. 4. Composites of precipitation (color, mm h^{-1}), precipitable water anomalies (black contours, mm), and 350-K PV (red contours, PVU) for the (a) AR-close and (b) AR-distant categories. The abscissa and ordinate indicate the relative longitude and latitude from the cutoff low (COL) center, respectively. Black and red contour intervals are 2.5 mm and 1 PVU, respectively. Purple rectangles indicate regions of the AR-rain area (long rectangle north of the cutoff low), the cutoff-NW-rain area (short rectangle north of the cutoff low), and the cutoff-SE-rain area (rectangle south of the cutoff low).

cutoff low center in the Hiroshima case (arrowed in Fig. 5).

2) VERTICAL STRUCTURES

The similarity between the composite analysis and the Hiroshima case is confirmed in the horizontal formation of the AR, the cutoff low, and the area of enhanced precipitation as well as in the vertical cross sections of environmental variables (Figs. 6–8). Figure 6 displays the vertical cross sections of specific humidity anomalies for the AR-close and AR-distant categories, and the Hiroshima case, along the NW–SE diagonal line of Fig. 5. The AR-close category composite and the Hiroshima case have a larger specific humidity anomaly above 800 hPa than the AR-distant category composite between -5° and -8° relative longitude (Rlon). This result is consistent with the result of H16 and indicates the importance of midtropospheric moisture. Note that moisture is higher in the lower troposphere in the western Pacific when compared with regions noted in studies of west coast landfalling ARs in the United States. Therefore, larger moisture anomalies in ARs are more frequently found in the midtroposphere, which contrasts with the composite shown in Ralph et al. (2005).

Similar vertical distributions are also observed in temperature anomalies along the cross sections (Fig. 7). In the Hiroshima case (Fig. 7c), a cold anomaly maximum associated with the cutoff low is located around the

cutoff low center. Hiroshima is located to the northwest of the cold anomaly. Because the midlevel cold anomaly extends from the cutoff low over the low-level warm moist air around Hiroshima, the atmosphere becomes thermodynamically unstable at $\sim 600\text{--}700$ hPa due to an increased lapse rate. In addition, potential temperature contours bend upward from Hiroshima toward the cutoff low center, indicating that an approach of the cutoff low induces upward motion with the isentropic upgliding effect (Hoskins et al. 1978). Similar characteristics are observed in the composite of the AR-close and AR-distant categories (Figs. 7a,b). The vertical gradients of temperature anomalies to the northwest of cutoff lows in the AR-distant category are smaller than those of the AR-close category, suggesting that atmospheres in the AR-distant category are more stable than those in the AR-close category to the northwest of the cutoff low. The bend angle of potential temperature contours to the northwest of the cutoff low center is slightly greater in the AR-close category than in the AR-distant category.

Figure 8 shows the vertical distributions of PV and vertical velocity along the cross sections. The high PV values attributed to the cutoff low and a large-scale trough associated with the AR are observed around 0° and -12° Rlon, respectively, in both the composite of the AR-close category (Fig. 8a) and the Hiroshima case (Fig. 8c). Upward motion in the AR-close category is located around the cutoff-NW-rain area extending to

FIG. 5. (a) As in Fig. 4a, but for the precipitation difference between the AR-close-category and the AR-distant-category cutoff lows (color, mm h^{-1} , only for regions with a 95% significance level), and the 350-K PV (green contours, PVU) and precipitable water anomalies (black contours, mm) in the AR-close category. Purple rectangles indicate regions of the AR-rain area (long rectangle) and the cutoff-NW-rain area (short rectangle) for the AR-close category. (b) Unconditional averaged precipitation (rainbow colors, mm h^{-1}), 350-K PV (red to blue colors, PVU), and precipitable water anomalies (red contours, mm, only for ≥ 10 mm) for the Hiroshima case. The red contour interval is 5 mm. The horizontal scale in (b) is adjusted to that in (a). Black arrows indicate the location of the heavy precipitation region in the Hiroshima case relative to the cutoff low center.

the northwest (around -10 Rlon), where the large-scale trough exists (Fig. 8a). Similar characteristics are observed in the Hiroshima case (Fig. 8c). In the AR-distant category, however, upward motion is located northwest of -8 Rlon and is very weak between -8 Rlon and the cutoff low center (Fig. 8b). The difference in upward motion distribution is consistent with that of QG forcing distribution shown in the next section.

c. Evaluation of QG forcing

In the previous section, we demonstrated a similarity between the AR-close category composite and the Hiroshima case, which suggests that enhanced precipitation commonly results from an interplay between ARs and cutoff lows. In this section, we investigate the role of large-scale forcing in vertical motion using the **Q**-vector form of the QG omega equation (Hoskins et al. 1978).

Figure 9 shows the horizontal distribution of the QG forcing term ($-2\nabla \cdot \mathbf{Q}$) at 600 hPa for composites of the AR-close and AR-distant categories and for the Hiroshima case. The areas of QG forcing for ascent are to the southeast of the jet axis and cutoff low in each figure. In contrast, the areas of QG forcing for descent are to the west of the cutoff low. The dynamically forced

ascending area to the southeast of the cutoff low corresponds to the cutoff-SE-rain area, which is consistent with numerous previous studies (Sadler 1976; Shimamura 1981, 1982; Kelley and Mock 1982; Chen and Chou 1994; Knippertz and Martin 2007; Nieto et al. 2008). The AR-rain area coincides with the dynamically forced ascending area to the southeast of the jet axis (Figs. 9a,b). QG forcing in the cutoff-NW-rain area of the AR-close category is for ascent, although QG forcing in the corresponding area of the AR-distant category is for descent (Figs. 9a,b). The horizontal distribution of QG forcing in the Hiroshima case is similar to that for the AR-close category, although the QG forcing region for descent is also located to the north of the cutoff low in the Hiroshima case (Fig. 9c). This dynamically forced descending area is likely caused by local variability in the jet stream.

Figure 10 shows the vertical cross sections of QG forcing. The distribution of dynamic forcing corresponds to that of upward motion (Fig. 8), which indicates the contribution of QG forcing to upward motion. The dynamically forced ascending areas around the cutoff-NW-rain area in the AR-close-category composite and around Hiroshima in the Hiroshima case extend farther to the southeast, in the direction of the center of the cutoff

FIG. 6. Vertical cross sections of the specific humidity anomalies of (a) the composite of the AR-close-category cases, (b) the composite of the AR-distant-category cases, and (c) the Hiroshima case, taken along a northwest–southeast diagonal line from Fig. 5. The abscissa shows the relative longitude from the cutoff low center, and the ordinate is the pressure (hPa). The dashed rectangle in (a) marks the location of the cutoff-NW-rain area, and the dashed line in (c) marks the location of Hiroshima.

low (mid- to lower troposphere), than in the AR-distant category.

This southeastward extension of the dynamically forced ascending area in the middle-to-lower troposphere around the cutoff-NW-rain area results from the counterplay of warm air advection near the AR and cold air advection from the northeast by the cutoff low.

Figures 11a and 11b show the horizontal distribution of the Laplacian of geostrophic temperature advection $[-(2R/p)\nabla^2(-\mathbf{V}_g \cdot \nabla T)]$, which can be obtained after expansion of the QG forcing term. Dynamic forcing for ascent associated with warm air advection by the AR is dominant around the cutoff-NW-rain area in the AR-close category. In contrast, dynamic forcing for descent

FIG. 7. As in Fig. 6, but showing temperature anomalies (color, K) and potential temperature (green contour, K) for (a) the composite of the AR-close-category cases, (b) the composite of the AR-distant-category cases, and (c) the Hiroshima case.

FIG. 8. As in Fig. 6, but showing the PV (color, PVU) and vertical velocity (black contours, hPa h^{-1} ; solid and dashed contours indicate downward and upward motion, respectively) for (a) the composite of the AR-close-category cases, (b) the composite of the AR-distant-category cases, and (c) the Hiroshima case. The vertical velocity contour intervals are 0.1 hPa h^{-1} in (a),(b) and 0.5 hPa h^{-1} in (c). Red contours indicate 200-, 500-, and 800-hPa isobars. The abscissa shows the relative longitude from the cutoff low center, and the ordinate shows the potential temperature (K).

associated with cold temperature advection by the cutoff low is dominant to the northwest of the cutoff low in the AR-distant category (purple rectangle to the northwest of the cutoff low in Fig. 11). Figures 11c and 11d show the difference between the QG forcing term and the

Laplacian of geostrophic temperature advection. This difference is small around the cutoff-NW-rain area in the AR-close category, indicating that dynamic forcing associated with temperature advection is dominant in the cutoff-NW-rain area in the AR-close category.

FIG. 9. (a),(b) As in Fig. 4, but showing the QG forcing term ($-2\nabla \cdot \mathbf{Q}$) at 600 hPa for the composite of the (a) AR-close-category and (b) AR-distant-category cutoff lows. (c) As in Fig. 5b, but showing the QG forcing term at 600 hPa for the Hiroshima case. For all the figures, color indicates the QG forcing term ($10^{-18} \text{ m s}^{-1} \text{ kg}^{-1}$). Note that the intervals of color in (c) are different from those in (a),(b). Contours show PV on the 350-K isentropic surface, with intervals of 1 PVU. The cutoff-NW-rain area is shown in (b),(c) as a reference. The cutoff-SE-rain area is shown in (b) as a reference.

FIG. 10. As in Fig. 6, but for the QG forcing term ($-2\nabla \cdot \mathbf{Q}$, color, $10^{-18} \text{ m s}^{-1} \text{ kg}^{-1}$) and temperature anomalies (contour, K) for (a) the composite of the AR-close-category cases, (b) the composite of the AR-distant-category cases, and (c) the Hiroshima case. Note that the intervals of color in (c) are different from those in (a), (b). The contour interval is 0.5 K.

The effect of warm air advection at 800–900 hPa associated with the AR (not shown) also appears as the lower-tropospheric warm anomaly around the cutoff-NW-rain area in the AR-close category composite (Fig. 7a). This contributes to destabilizing the atmosphere around the cutoff-NW-rain area.

In summary, the results of this and the previous subsections indicate that enhanced precipitation in the cutoff-NW-rain area can be caused by the following factors: the deep moist layer associated with the AR, destabilization and the isentropic up-gliding effect associated with the cutoff low, and reduced descending forcing to the northwest of the cutoff low by warm air advection associated with an AR, which make the instability and up-gliding effect in that region more effective. Such factors related to ARs and cutoff lows induce a favorable environment for enhanced precipitation to the northwest of the cutoff low.

d. Precipitation sensitivity to the distance between an AR and a cutoff low

The above results indicate that precipitation enhancement in the cutoff-NW-rain area is associated with the interplay between an AR and a cutoff low. In this subsection, we investigate the sensitivity of the location of enhanced precipitation to the distance between an AR and a cutoff low to show the effect of the interplay in enhancing precipitation.

The specific procedure is as follows. We first subdivide the AR-close category into three classes based on the distance between the AR axis and the cutoff low center:

the 5° – 7.5° , 7.5° – 10° , and 10° – 12.5° classes. The distance criterion for the “AR-distant category” is set to 15° – 17.5° in this analysis, instead of 12.5° – 20° as in previous subsections. Precipitation enhancement through the interplay is expected in the three classes, although the distance between the AR and the cutoff low is different. We then compare each class with the AR-distant category to investigate the sensitivity of locations of the enhanced precipitation area to the distance between ARs and cutoff lows. The location should be insensitive to changes in distance if the precipitation enhancement at the location results from the interplay between an AR and a cutoff low. Conversely, the location should move with a change in distance if the precipitation enhancement is the result of only the ARs.

Figure 12 shows the results of these analyses. In all the classes, significantly enhanced precipitation areas are located to the south of the AR axis and northwest of the cutoff low center specifically at around (-5° Rlon, 5° Rlat). These areas correspond to the cutoff-NW-rain area. The significant level is 80% for the 10° – 12.5° class. The limited enhancement in the 10° – 12.5° class is likely caused by the smaller amount of precipitable water because of the location of the AR. From this analysis, we confirm that the cutoff-NW-rain area does not move with the location of AR, indicating that enhanced precipitation in this area is associated with the proposed interplay.

In contrast, areas of significantly enhanced precipitation located to the north of the AR axis, which correspond to the AR-rain area, shift to the north as the

FIG. 11. As in Fig. 9, but showing (a),(b) the Laplacian of geostrophic temperature advection and (c),(d) the difference between the QG forcing term ($-2\mathbf{\nabla} \cdot \mathbf{Q}$) and the Laplacian of geostrophic temperature advection (color, $10^{-18} \text{ m s}^{-1} \text{ kg}^{-1}$) at 600 hPa for (a),(c) the composite of the AR-close-category cases and (b),(d) the composite of the AR-distant-category cases. Contours show PV on the 350-K isentropic surface, with intervals of 1 PVU.

distance between ARs and cutoff lows increases (Fig. 12). This result suggests that precipitation enhancement in the AR-rain area is attributed to the trough associated with the AR.

5. Discussion and conclusions

The results of this study indicate that precipitation enhancement associated with the interplay between ARs and cutoff lows is common, and the disastrous 2014 rainfall event in Hiroshima was an extreme case of such a phenomenon. Considering that cutoff lows and ARs in the western North Pacific region have little impact near the surface, precipitation enhancement associated with the interplay between ARs and cutoff lows has been underestimated in previous analyses for humid regions, such as those of summertime precipitation in Japan, which have focused instead on the characteristics of the lower troposphere. From the perspective of the reduction of risk due to disasters, this study emphasizes the need to better understand the impact of upper tropospheric phenomena, such as cutoff lows, on enhanced precipitation.

In this study, a statistical investigation of the mechanism for precipitation enhancement involving the interplay between ARs and upper tropospheric cutoff lows has been investigated. We constructed composites of cutoff lows close to the AR (AR-close category), in which the interplay was thought to enhance precipitation, and distant from the AR (AR-distant category), in which the interplay was thought to hardly affect precipitation. A comparison between composites shows an enhanced precipitation area located to the northwest of the cutoff low and to the south of the AR axis in the AR-close category (cutoff-NW-rain area), in addition to an enhanced precipitation area associated with the AR (AR-rain area). The horizontal formation of the AR, the cutoff low, and areas of enhanced precipitation are schematically illustrated in Fig. 13. We are able to confirm a deep moist layer, an unstable temperature profile, and QG forcing for ascent in the cutoff-NW-rain area in the AR-close category. The horizontal formation and dynamic and thermodynamic characteristics are observed to coincide with those characterizing the flood event that occurred in Hiroshima, Japan, on 19 August 2014. These results indicate that the enhanced precipitation

FIG. 12. As in Fig. 5a, but for the precipitation difference between the AR-close-category and AR-distant-category cutoff lows for the (a) 5° – 7.5° , (b) 7.5° – 10° , and (c) 10° – 12.5° classes [color, mm h^{-1} , applicable only for regions with a 95% significance level in (a), (b), and an 80% significance level in (c)]. Red dotted lines indicate the axis of the AR.

in the cutoff-NW-rain area is associated with their interplay.

The above conclusion is obtained from discussions on whether an AR exists near a cutoff low with the cutoff-low-centered composites. Consistent results can be obtained based on whether a cutoff low exists near an AR with AR-centered composites (not shown). This result indicates the robustness of enhanced precipitation through the interplay between ARs and cutoff lows.

Because most of the cutoff lows in this analysis are located over the ocean (Fig. 2), the mechanism of precipitation enhancement through the interplay is not limited to the Hiroshima case but is rather a common

mechanism for precipitation enhancement. In other words, the Hiroshima case is an extreme precipitation event that resulted from this interplay.

The large amount of free tropospheric moisture associated with an AR is an important factor in the enhancement of precipitation *via* the interplay between an AR and a cutoff low. The large (small) specific humidity difference between the AR-close and AR-distant categories above (below) 800 hPa around the cutoff-NW-rain area (Fig. 6), which is consistent with the H16 results, indicates the importance of free tropospheric moisture. Previous studies have also illustrated the importance of midtropospheric moisture to

FIG. 13. Schematic maps showing the positions of a cutoff low, an AR, a trough associated with the AR, the mid-Pacific trough, and precipitation areas.

ensure intense precipitation (Bretherton et al. 2004; Takayabu et al. 2006; Hirota et al. 2014; Hamada et al. 2015).

The roles of cutoff lows on the enhancement of precipitation associated with this interplay are different from those of upper tropospheric phenomena shown in most previous studies. Most such studies emphasized the effects of upper-tropospheric disturbance in the transport of moisture (e.g., Maddox et al. 1979). Piaget et al. (2015) showed that moisture associated with a rainfall event in the northern Alps is collected by a cutoff low over West Africa and then transported by synoptic flows. Froidevaux and Martius (2016) and de Vries et al. (2018) also focused on moisture transport associated with upper tropospheric cutoff lows or PV streamers. Martius et al. (2013) investigated a rainfall event in Pakistan and showed the importance of the effect of an upper tropospheric PV anomaly for inducing a wind field directed toward a mountain. On the other hand, Corbosiero et al. (2009) showed the interaction between a cutoff low and a tropical cyclone causing heavy rainfall in the southwestern United States. This is similar to the interplay shown in this study at a point where moist plumes associated with the tropical cyclone provide moisture and the cutoff low induces upward motion.

The small difference in the absolute values of precipitation between the AR-close and AR-distant categories in the cutoff-NW-rain area can be the result of temporal and spatial smoothing during the composite analyses. Therefore, it is important to confirm the statistically significant difference even if the absolute values are small. The quantitative evaluation of precipitation enhancement through the interplay described herein requires other approaches, such as sensitivity studies using a numerical model, which may form the subject of future work.

Acknowledgments. We are sincerely grateful to three anonymous reviewers and the editor for critical reading of the original manuscript and providing useful comments. This research was supported by the 8th RA of the Japan Aerospace Exploration Agency (JAXA) Precipitation Measuring Mission (PMM) science, the Environment Research and Technology Development Fund (2-1503) of the Environmental Restoration and Conservation Agency, the University of Tokyo through a project “Research hub for the big data analysis of global water cycle and precipitation in changing climate,” and JSPS KAKENHI Grant 15H02132. The GSMaP data were produced and distributed by the Earth Observation Research Center, JAXA.

REFERENCES

- Abatzoglou, J. T., 2016: Contribution of cutoff lows to precipitation across the United States. *J. Appl. Meteor. Climatol.*, **55**, 893–899, <https://doi.org/10.1175/JAMC-D-15-0255.1>.
- Aonashi, M., and Coauthors, 2009: GSMaP passive microwave precipitation retrieval algorithm: Algorithm description and validation. *J. Meteor. Soc. Japan*, **87A**, 119–136, <https://doi.org/10.2151/jmsj.87A.119>.
- Bretherton, C. S., M. E. Peters, and L. E. Back, 2004: Relationships between water vapor path and precipitation over the tropical oceans. *J. Climate*, **17**, 1517–1528, [https://doi.org/10.1175/1520-0442\(2004\)017<1517:RBWVPA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1517:RBWVPA>2.0.CO;2).
- Chen, C.-S., W.-C. Chen, Y.-L. Chen, P.-L. Lin, and H.-C. Lai, 2005: Investigation of orographic effects on two heavy rainfall events over southwestern Taiwan during the Mei-yu season. *Atmos. Res.*, **73**, 101–130, <https://doi.org/10.1016/j.atmosres.2004.07.005>.
- Chen, G. T.-J., and L.-F. Chou, 1994: An investigation of cold vortices in the upper troposphere over the western North Pacific during the warm season. *Mon. Wea. Rev.*, **122**, 1436–1448, [https://doi.org/10.1175/1520-0493\(1994\)122<1436:AIOCVI>2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122<1436:AIOCVI>2.0.CO;2).
- Chen, G. T.-J., and I.-M. Tang, 2004: Formation and characteristics of a summertime hailstorm over northern Taiwan. *J. Meteor. Soc. Japan*, **82**, 695–709, <https://doi.org/10.2151/jmsj.2004.695>.
- Corbosiero, K. L., M. J. Dickinson, and L. F. Bosart, 2009: The contribution of eastern North Pacific tropical cyclones to the rainfall climatology of the southwest United States. *Mon. Wea. Rev.*, **137**, 2415–2435, <https://doi.org/10.1175/2009MWR2768.1>.
- de Vries, A. J., H. G. Ouwersloot, S. B. Feldstein, M. Riemer, A. M. El Kenawy, M. F. McCabe, and J. Lelieveld, 2018: Identification of tropical–extratropical interactions and extreme precipitation events in the Middle East based on potential vorticity and moisture transport. *J. Geophys. Res. Atmos.*, **123**, 861–881, <https://doi.org/10.1002/2017JD027587>.
- Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan, 2011: Atmospheric rivers, floods, and the water resources of California. *Water*, **3**, 445–478, <https://doi.org/10.3390/w3020445>.
- Favre, A., B. Hewitson, C. Lennard, R. Cerezo-Mota, and M. Tadross, 2013: Cutoff lows in the South Africa region and their contribution to precipitation. *Climate Dyn.*, **41**, 2331–2351, <https://doi.org/10.1007/s00382-012-1579-6>.
- Froidevaux, P., and O. Martius, 2016: Exceptional integrated vapour transport toward orography: An important precursor to severe floods in Switzerland. *Quart. J. Roy. Meteor. Soc.*, **142**, 1997–2012, <https://doi.org/10.1002/qj.2793>.
- Giannakaki, P., and O. Martius, 2016: Synoptic-scale flow structures associated with extreme precipitation events in northern Switzerland. *Int. J. Climatol.*, **36**, 2497–2515, <https://doi.org/10.1002/joc.4508>.
- Gimeno, L., R. Nieto, M. Vázquez, and D. A. Lavers, 2014: Atmospheric rivers: A mini-review. *Front. Earth Sci.*, **2**, 2, <https://doi.org/10.3389/feart.2014.00002>.
- Guan, B., and D. E. Waliser, 2015: Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies. *J. Geophys. Res. Atmos.*, **120**, 12 514–12 535, <https://doi.org/10.1002/2015JD024257>.
- Hamada, A., Y. N. Takayabu, C. Liu, and E. J. Zipser, 2015: Weak linkage between the heaviest rainfall and tallest storms. *Nat. Commun.*, **6**, 6213, <https://doi.org/10.1038/ncomms7213>.
- Harada, Y., and Coauthors, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability.

- J. Meteor. Soc. Japan*, **94**, 269–302, <https://doi.org/10.2151/jmsj.2016-015>.
- Hardy, S., D. M. Schultz, and G. Vaughan, 2017: The 23–26 September 2012 U.K. floods: Using PV surgery to quantify sensitivity to upper-level forcing. *Mon. Wea. Rev.*, **145**, 4055–4079, <https://doi.org/10.1175/MWR-D-16-0434.1>.
- Hirota, N., Y. N. Takayabu, M. Watanabe, M. Kimoto, and M. Chikira, 2014: Role of convective entrainment in spatial distributions of and temporal variations in precipitation over tropical oceans. *J. Climate*, **27**, 8707–8723, <https://doi.org/10.1175/JCLI-D-13-00701.1>.
- , —, M. Kato, and S. Arakane, 2016: Roles of an atmospheric river and a cutoff low on 19 August 2014. *Mon. Wea. Rev.*, **144**, 1145–1160, <https://doi.org/10.1175/MWR-D-15-0299.1>.
- Holton, J. R., 2004: *An Introduction to Dynamic Meteorology*. 4th ed. Elsevier, 529 pp.
- Horinouchi, T., 2014: Influence of upper tropospheric disturbances on the synoptic variability of precipitation and moisture transport over summertime East Asia and the northwestern Pacific. *J. Meteor. Soc. Japan*, **92**, 519–541, <https://doi.org/10.2151/jmsj.2014-602>.
- Hoskins, B. J., I. Draghi, and H. C. Davies, 1978: A new look at the ω -equation. *Quart. J. Roy. Meteor. Soc.*, **104**, 31–38, <https://doi.org/10.1002/qj.49710443903>.
- , M. E. McIntyre, and A. W. Robertson, 1985: On the use and significance of isentropic potential vorticity maps. *Quart. J. Roy. Meteor. Soc.*, **111**, 877–946, <https://doi.org/10.1002/qj.49711147002>.
- Juneng, L., F. T. Tangang, and C. J. C. Reason, 2007: Numerical case study of an extreme rainfall during 9–11 December 2004 over the east coast of Peninsular Malaysia. *Meteor. Atmos. Phys.*, **98**, 81–98, <https://doi.org/10.1007/s00703-006-0236-1>.
- Kamae, Y., W. Mei, S.-P. Xie, M. Naoi, and H. Ueda, 2017: Atmospheric rivers over the northwestern Pacific: Climatology and interannual variability. *J. Climate*, **30**, 5605–5619, <https://doi.org/10.1175/JCLI-D-16-0875.1>.
- Kato, T., 2006: Structure of the band-shaped precipitation system inducing the heavy rainfall observed over the northern Kyushu, Japan on 29 June 1999. *J. Meteor. Soc. Japan*, **84**, 129–153, <https://doi.org/10.2151/jmsj.84.129>.
- Kelley, W. E., Jr., and D. R. Mock, 1982: A diagnostic study of upper tropospheric cold lows over the western North Pacific. *Mon. Wea. Rev.*, **110**, 471–480, [https://doi.org/10.1175/1520-0493\(1982\)110<0471:ADSOUT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0471:ADSOUT>2.0.CO;2).
- Knippertz, P., and J. E. Martin, 2005: Tropical plumes and extreme precipitation in subtropical and tropical West Africa. *Quart. J. Roy. Meteor. Soc.*, **131**, 2337–2365, <https://doi.org/10.1256/qj.04.148>.
- , and —, 2007: A Pacific moisture conveyor belt and its relationship to a significant precipitation event in the semiarid southwestern United States. *Wea. Forecasting*, **22**, 125–144, <https://doi.org/10.1175/WAF963.1>.
- , and H. A. Wernli, 2010: Lagrangian climatology of tropical moisture exports to the Northern Hemispheric extratropics. *J. Climate*, **23**, 987–1003, <https://doi.org/10.1175/2009JCLI3333.1>.
- Kobayashi, S., and Coauthors, 2015: The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*, **93**, 5–48, <https://doi.org/10.2151/jmsj.2015-001>.
- Kubota, T., and Coauthors, 2007: Global Precipitation Map using satellite borne microwave radiometers by the GSMAp Project: Production and validation. *IEEE Trans. Geosci. Remote Sens.*, **45**, 2259–2275, <https://doi.org/10.1109/TGRS.2007.895337>.
- Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso- α scale aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115–123, <https://doi.org/10.1175/1520-0477-60.2.115>.
- Martius, O., E. Zenklusen, C. Schierz, and H. C. Davies, 2006: Episodes of Alpine heavy precipitation with an overlying elongated stratospheric intrusion: A climatology. *Int. J. Climatol.*, **26**, 1149–1164, <https://doi.org/10.1002/joc.1295>.
- , and Coauthors, 2013: The role of upper-level dynamics and surface processes for the Pakistan flood of July 2010. *Quart. J. Roy. Meteor. Soc.*, **139**, 1780–1797, <https://doi.org/10.1002/qj.2082>.
- Massacand, A. C., H. Wernli, and H. C. Davies, 1998: Heavy precipitation on the Alpine southside: An upper-level precursor. *Geophys. Res. Lett.*, **25**, 1435–1438, <https://doi.org/10.1029/98GL50869>.
- Moore, B. J., P. J. Neiman, F. M. Ralph, and F. E. Barthold, 2012: Physical processes associated with heavy flooding rainfall in Nashville, Tennessee, and vicinity during 1–2 May 2010: The role of an atmospheric river and mesoscale convective systems. *Mon. Wea. Rev.*, **140**, 358–378, <https://doi.org/10.1175/MWR-D-11-00126.1>.
- Mundhenk, B. D., E. A. Barnes, and E. D. Maloney, 2016: All-season climatology and variability of atmospheric rivers frequencies over the North Pacific. *J. Climate*, **29**, 4885–4903, <https://doi.org/10.1175/JCLI-D-15-0655.1>.
- Nieto, R., M. Sprenger, H. Wernli, R. M. Trigo, and L. Gimeno, 2008: Identification and climatology of cutoff lows near the tropopause. *Ann. N. Y. Acad. Sci.*, **1146**, 256–290, <https://doi.org/10.1196/annals.1446.016>.
- Oakley, N. S., and K. T. Redmond, 2014: A climatology of 500-hPa closed lows in the northeastern Pacific Ocean, 1948–2011. *J. Appl. Meteor. Climatol.*, **53**, 1578–1592, <https://doi.org/10.1175/JAMC-D-13-0223.1>.
- Piaget, N., P. Froidevaux, P. Giannakaki, F. Gierth, O. Martius, M. Riemer, G. Wolf, and C. M. Grams, 2015: Dynamics of a local Alpine flooding event in October 2011: Moisture source and large-scale circulation. *Quart. J. Roy. Meteor. Soc.*, **141**, 1922–1937, <https://doi.org/10.1002/qj.2496>.
- Ralph, F. M., P. J. Neiman, and G. A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.*, **132**, 1721–1745, [https://doi.org/10.1175/1520-0493\(2004\)132<1721:SACAO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1721:SACAO>2.0.CO;2).
- , —, and R. Rotunno, 2005: Dropsonde observations in low-level jets over the northeastern Pacific Ocean from CALJET-1998 and PACJET-2001: Mean vertical-profile and atmospheric-river characteristics. *Mon. Wea. Rev.*, **133**, 889–910, <https://doi.org/10.1175/MWR2896.1>.
- , —, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White, 2006: Flooding on California's Russian river: Role of atmospheric rivers. *Geophys. Res. Lett.*, **33**, L13801, <https://doi.org/10.1029/2006GL026689>.
- , —, G. N. Kiladis, K. Weikmann, and D. W. Reynolds, 2011: A multiscale observational case study of a Pacific atmospheric river exhibiting tropical–extratropical connections and a mesoscale frontal wave. *Mon. Wea. Rev.*, **139**, 1169–1189, <https://doi.org/10.1175/2010MWR3596.1>.
- Sadler, J. C., 1976: A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.*, **104**, 1266–1278, [https://doi.org/10.1175/1520-0493\(1976\)104<1266:AROTTU>2.0.CO;2](https://doi.org/10.1175/1520-0493(1976)104<1266:AROTTU>2.0.CO;2).
- Sakamoto, K., and M. Takahashi, 2005: Cut off and weakening processes of an upper cold low. *J. Meteor. Soc. Japan*, **83**, 817–834, <https://doi.org/10.2151/jmsj.83.817>.

- Shimamura, M., 1981: The upper-tropospheric cold lows in the Northwestern Pacific as revealed in the GMS satellite data. *Geophys. Mag.*, **39**, 119–156.
- , 1982: An application of GMS satellite data in the analysis of the upper cold low in the western North Pacific. *Geophys. Mag.*, **40**, 113–152.
- Sugi, M., and M. Kanamitsu, 1982: A study of a subtropical upper level cyclone using JMA operational forecast model. *J. Meteor. Soc. Japan*, **60**, 932–946, https://doi.org/10.2151/jmsj1965.60.4_932.
- Takayabu, Y. N., J. Yokomori, and K. Yoneyama, 2006: A diagnostic study on interactions between atmospheric thermodynamic structure and cumulus convection over the tropical western Pacific Ocean and over the Indochina peninsula. *J. Meteor. Soc. Japan*, **84A**, 151–169, <https://doi.org/10.2151/jmsj.84A.151>.
- Tu, C.-C., Y.-L. Chen, C.-S. Chen, P.-L. Lin, and P.-H. Lin, 2014: A comparison of two heavy rainfall events during the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) 2008. *Mon. Wea. Rev.*, **142**, 2436–2463, <https://doi.org/10.1175/MWR-D-13-00293.1>.
- Tsuguti, H., and T. Kato, 2014: Contributing factors of the heavy rainfall event at Amami-Oshima Island, Japan, on 20 October 2010. *J. Meteor. Soc. Japan*, **92**, 163–183, <https://doi.org/10.2151/jmsj.2014-202>.
- Wen, D., Y. Li, D.-L. Zhang, L. Xue, and N. Wei, 2018: A statistical analysis of tropical upper-tropospheric trough cells over the western North Pacific during 2006–15. *J. Appl. Meteor. Climatol.*, **57**, 2469–2483, <https://doi.org/10.1175/JAMC-D-18-0003.1>.
- Wernli, H., and M. Sprenger, 2007: Identification and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical tropopause. *J. Atmos. Sci.*, **64**, 1569–1586, <https://doi.org/10.1175/JAS3912.1>.
- Yokoyama, C., Y. N. Takayabu, and T. Horinouchi, 2017: Precipitation characteristics over East Asia in early summer: Effects of the subtropical jet and lower-tropospheric convective instability. *J. Climate*, **30**, 8127–8147, <https://doi.org/10.1175/JCLI-D-16-0724.1>.
- Zhang, C., Q. Zhang, Y. Wang, and X. Liang, 2008: Climatology of warm season cold vortices in East Asia: 1979–2005. *Meteor. Atmos. Phys.*, **100**, 291–301, <https://doi.org/10.1007/s00703-008-0310-y>.
- Zhu, Y., and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric rivers. *Mon. Wea. Rev.*, **126**, 725–735, [https://doi.org/10.1175/1520-0493\(1998\)126<0725:APAFMF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<0725:APAFMF>2.0.CO;2).