Climatology of Anticyclonic and Cyclonic Rossby Wave Breaking on the Dynamical Tropopause in the Southern Hemisphere

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ABSTRACT

The characteristics of the climatological distribution of the anticyclonic (LC1) and cyclonic (LC2) Rossby wave breaking (RWB) in the Southern Hemisphere (SH) are investigated by calculating the occurrence frequency of the LC1- and LC2-like stratospheric potential vorticity (PV) streamers in the SH during the austral summer [December–February (DJF)] and wintertime [June–August (JJA)] on several isentropic surfaces by using the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) daily dataset. The results show that 1) on the equatorward flank of the climatological midlatitude jet (MLJ), the LC1-like PV streamers are frequently found over the central oceanic regions, whereas the LC2-like PV streamers are almost absent. On the poleward flank of the climatological MLJ, both types of PV streamers are frequently observed and the LC2-like PV streamers predominate; 2) the regions where the occurrences of the PV streamers are frequent overlap the weak zonal wind regions; and 3) in austral winter, a “double-jet” setting is evident in two regions of the SH [the double-jet upstream (DU) and the split-jet region]. In the double-jet setting regions, the LC1-like PV streamers are frequently found both in the DU and the split-jet regions, while the occurrence of the LC2-like PV streamers is frequent in the split-jet region but is rather infrequent in the DU region.

1. Introduction

From the “potential vorticity (PV)–theta” perspective, the Rossby wave breaking (RWB) means the rapid and irreversible deformation of PV contours on isentropic surfaces over a longitudinally confined region (McIntyre and Palmer 1983, 1984). The RWB events in the upper troposphere are associated with pronounced excursions of high-PV stratospheric air intruding the troposphere and/or low-PV tropospheric air intruding the stratosphere on isentropic surfaces. Frequently, the high-PV air is elongated to a tonguelike shape and further stretched into narrow filaments retaining only a thin connection to the main body of the stratospheric air. These structures are called stratospheric PV streamers (Appenzeller and Davies 1992). Sometimes the PV streamers roll up or break up from the main stratospheric body and eventually form a distinct cutoff. The PV streamers and cutoffs can be considered PV anomalies (departure from the background), which can impact the large-scale atmosphere circulation both in the extratropics (e.g., Esler and Haynes 1999) and the tropics (e.g., Kiladis 1998). Owing to the irreversible nature of the RWB, it tends to homogenize the isentropic PV distribution and drives a cascade of enstrophy to small scales over wave-breaking regions. The RWB events along the tropopause are also important to the mass exchange between the troposphere and the stratosphere along quasi-horizontal isentropic surfaces (Holton et al. 1995).

The RWB events in observations have been widely investigated, from case studies (e.g., Postel and Hitchman 2001; Peters and Waugh 2003) to climatological spatial distributions (e.g., Postel and Hitchman 1999; Wernli
and Sprenger 2007; Berrisford et al. 2007; Hitchman and Huesmann 2007). Usually, the RWB events are categorized as two theoretical distinct paradigms: the anticyclonic (LC1) and the cyclonic (LC2) wave breaking (Thorncroft et al. 1993), which are, at least partly, responsible for many important atmospheric circulation patterns such as the vacillation of the zonal-mean zonal wind (e.g., Akahori and Yoden 1997), the formation of the North Atlantic Oscillation (NAO; Benedict et al. 2004; Rivière and Orlanski 2007; Strong and Magnusdottir 2008; Kunz et al. 2009), and the variation of storm tracks (Orlanski 2003, 2005). The schematic diagram for the structures of these two types of RWB events in the Southern Hemisphere (SH) is shown in Fig. 1. The LC1 (LC2) wave breaking is characterized by stratospheric PV streamers NW–SE (NE–SW) tilted with an anticyclonic (cyclonic) advection of the stratospheric high and tropospheric low PV air. The NW–SE (NE–SW) tilted stratospheric PV streamer shown in Fig. 1 is referred to as the LC1 (LC2)-like PV streamer in this text.

An intriguing study on the climatological distribution of the RWB events is to identify the RWB events from the synoptic scale to the planetary scale. Thus, although the resolution of the data may not be fine enough to capture finer-scale features of the RWB, it is sufficient for the present study.

2 The wave-breaking events are also identified as four paradigms in some studies (e.g., Esler and Haynes 1999).

2. Data and methodology

a. Data

The ERA-40 daily (at 1200 UTC; Uppala et al. 2005) PV, zonal wind, and temperature fields were used in this study. The data cover the time period from 1 September 1957 to 31 August 2002 and are archived on 23 pressure levels spanning from 1000 to 1 hPa with a 2.5° × 2.5° horizontal resolution. This study is to identify the RWB events from the synoptic scale to the planetary scale. Thus, although the resolution of the data may not be fine enough to capture finer-scale features of the RWB, it is sufficient for the present study.

b. Choice of isentropic surfaces

The climatological distribution of the zonal wind on the dynamical tropopause is shown in Fig. 2 for the austral summer [December–February (DJF)] and winter [June–August (JJA)]. There is only one eddy-driven midlatitude jet (MLJ; ~120°W–150°E) in summer.
stretching from the eastern South Pacific Ocean across the South Atlantic Ocean and the South Indian Ocean. However, during austral winter, the features of the basic flow on the dynamical tropopause are complicated by the additional presence of the strong subtropical jet (STJ) over the South Indian and Pacific Oceans. In the mid-latitude band, a double-jet setting is evident in two regions (the bottom panel of Fig. 2). One region is located over the South Indian Ocean (~60°–120°E), where the MLJ is located upstream and to the south of the STJ. This is similar to the double-jet upstream (DU) configuration discussed by Peters and Waugh (2003). Hence, this region is referred to as the “DU” region hereafter. The other region is located over the South Pacific Ocean (~130°E–140°W), where the strong STJ is paralleled by a weak MLJ with a distinct zonal wind minimum.

![Diagram of Climatological-mean zonal wind speed](image_url)

*Fig. 2. Climatological-mean zonal wind speed (shaded) on the dynamical tropopause (the ~2-PVU isosurface) and the intersections (dashed line) of the isentropic surface with the dynamical tropopause in DJF (the isentropic surfaces are 350, 322, and 310 K) and JJA (the isentropic surfaces are 340, 325, 320, 315, 310, and 303 K). The unit of zonal wind speed is in meters per second.*
between these two jets. This flow configuration is well known as the SH split jet (Bals-Elscholz et al. 2001). The SH background flow during DJF and JJA is very distinctive. Therefore, the climatological distribution of the RWB is examined for only these months.

In this study, following Martius et al. (2007), the LC1/LC2 RWB events are represented by the LC1/LC2-like PV streamers, which are objectively identified along the intersections of several isentropic surfaces with the dynamical tropopause. The climatological spatial distribution of the LC1/LC2 RWB is assessed by the occurrence frequency of the LC1/LC2-like PV streamer.

In DJF months, the PV streamers are identified on the 350-, 322-, and 310-K isentropic surfaces. These three isentropic surfaces are chosen because their intersections with the tropopause are embedded in representative zonal wind configurations—that is, the equatorward side, the central axis, and the poleward side of the climatological MLJ (see the top-left panel of Fig. 2). Therefore, the intersection of 350 K (310 K) is located in the regions where anticyclonic (cycloonic) shears dominate. The intersection of 322 K is located in the transitional regions between the anticyclonic and cycloonic shear. In JJA months, for a better representation of the climatological distribution of the RWB in such complicated basic flow environments, the PV streamers are identified on six different isentropic surfaces, which are the 340-, 325-, 320-, 315-, 310-, and 303-K isentropic surfaces, respectively. Their intersections almost evenly cover the climatological double-jet setting regions (see the top-right panel of Fig. 2). According to the distribution of jets, for an easy reference, the SH is divided into two sectors: the STJ sector (−60°E–120°W) and the MLJ sector (−90°W–60°E, see the bottom panel of Fig. 2) in JJA months. In the STJ sector, the intersection of 340 K is located at the central axis of the climatological STJ, the intersections of 325 and 320 K are located at the poleward side of the climatological STJ, the intersections of 310 and 303 K are located at the equatorward and poleward side of the climatological MLJ, respectively, and the intersection of 315 K is situated right at the zonal wind minimum between the STJ and the MLJ. In the MLJ sector, the intersections of 340, 325, and 320 K (310 and 303 K) are located at the equatorward (poleward) side of the climatological MLJ. The intersection of 315 K is interventive. For identifying the PV streamers, the daily PV fields are interpolated from pressure levels onto the aforementioned isentropic surfaces. To reduce possible subsynoptic-scale wave disturbances, the interpolated PV field is filtered using a Fourier transform and only the information from zonal waves 0 to 15 is retained.

c. Approach for identifying the LC1/LC2-like PV streamer

The approach for identifying the LC1/LC2-like PV streamers on isentropic surfaces consists of the following steps:

1) The meridional PV gradients for the gridpoints along the –2-PVU contours are calculated. A gridpoint along the –2-PVU contours is defined as a gridpoint with a PV value greater than or equal to –2 PVU and if at least one of its neighboring gridpoints has a PV value less than –2 PVU.

2) Any reversal in the sign of the meridional PV gradients is identified. A wave-breaking event is defined for a gridpoint if there is a reversal in the sign of the meridional PV gradient (PV$_x$ < 0) at that gridpoint; and that gridpoint is labeled as a “base gridpoint” (such as point A in Fig. 1).

3) The base gridpoints are rechecked to exclude the reversed meridional PV gradients induced by the isolated blockings or the cutoffs. This is done by a contour-searching algorithm that can distinguish whether the base gridpoints are encircled by a localized, closed –2-PVU contour. If so, those base gridpoints are considered as part of an isolated blocking or cutoff and thus abandoned. It is known that the isolated blockings and cutoffs are closely related to the RWB events (Thorncroft et al. 1993). However, they are excluded from the RWB events defined in this analysis because it is difficult to tell their breaking types.

4) There is a difference between the LC1 and LC2 RWB events in the zonal PV gradients (PV$_x$) of the base gridpoints: for the LC1 RWB events, the signs of PV$_x$ at the base gridpoints are negative (PV$_x$ < 0), whereas for the LC2 RWB events, the signs of PV$_x$ at the base gridpoints are positive (PV$_x$ > 0, see Fig. 1). Therefore, the residual base gridpoints are further classified into LC1 (PV$_x$ < 0) and LC2 (PV$_x$ > 0) types according to the signs of PV$_x$. When we draw a line from the base gridpoints (such as point A in Fig. 1) to the equator along a longitude, the line will intersect the –2-PVU contour once again. These intersected points (such as point B in Fig. 1) are defined as the “end gridpoints.” For the LC1 (LC2) base gridpoints, if the area on the western (eastern) side of the direct connection between the base gridpoints and end gridpoints is surrounded by the –2-PVU contour, it is identified as a LC1 (LC2) PV streamer (the hatched area in Fig. 1), which represents the LC1 (LC2) RWB events. All the gridpoints within the LC1 (LC2) PV streamers are defined as LC1 (LC2) “wave-breaking gridpoints.” To ensure
the spatial scale of the PV streamers is not too small, only the PV streamers with at least five wave-breaking gridpoints are retained.

To illustrate the PV streamers identified by this approach, the synoptic maps for the PV in two austral winter days (5 August 1996 and 20 July 2000) are shown in Fig. 3. The dashed lines denote the $-2$-PVU contours on the 315-K isentropic surface, and the shaded areas denote the LC1/LC2-like PV streamers identified by the algorithm. During these two days, the SH is dominated by the LC1 and LC2 RWB events, respectively. Two main features should be noted here. First, there is a small isolated tropospheric cutoff within the LC1-like PV streamer near South America, which is encircled by a localized closed $-2$-PVU contour (top-left panel in Fig. 3), indicating that our approach only detects the PV streamers to represent the RWB events, with the isolated blockings and cutoffs excluded. Second, on 20 July 2000, the PV streamers have a purely LC1- or LC2-like shape, and thus they are identified to be either LC1 or LC2. However, on 5 August 1996, there are several PV streamers associated with the LC1 and LC2 characteristics simultaneously (e.g., the PV streamer over the South Indian Ocean and the PV streamer near Australia). Based on the algorithm, the western part of the PV streamer over the South Indian Ocean is identified to be LC1, whereas the eastern part of this

![Fig. 3. Synoptic maps of the filtered $-2$-PVU contours (dashed lines) on the 315-K isentropic surface on 5 Aug 1996 and 20 Jul 2000. The shaded regions correspond to stratospheric PV streamers for the LC1/LC2 Rossby wave-breaking events.](image-url)
streamer is identified to be LC2 (top panel of Fig. 3). Therefore, an LC1 streamer and an LC2 streamer can be simultaneously identified on the same PV streamer. Some further discussions about the PV streamer detection approach are given in the last section of the text.

3. Climatology of the LC1- and LC2-like PV streamers

The climatological distributions of the LC1- and LC2-like PV streamers during the austral summer and winter are discussed in this section. The algorithm described above is applied to every time point of the dataset for the given isentropic surfaces. Then, the frequency of occurrence (%) of the streamers is calculated, indicating the percentage of time that either a LC1- or LC2-like PV streamer is found at a certain gridpoint.

a. DJF

The occurrence frequency of the PV streamers (denoted by the shaded area and thin contours) and the climatological zonal wind speed (denoted by the bold contours) on the 350-, 322-, and 310-K isentropic surfaces for DJF are shown in Fig. 4.

On the 350-K isentropic surface, the PV streamers are detected at the equatorward side of the climatological MLJ. The occurrences of the 350-K PV streamers are dominated by the LC1, and the LC2-like PV streamers are almost absent. Only in the zonal wind minimum at the eastern South Pacific Ocean can we find some trace of the LC2-like PV streamers (<2%). The occurrences of the LC1-like PV streamers are very frequent along ~30°S, with a notable minimum over the entrance region of the MLJ near South America. There are three regional maxima located near the middle of the oceans [South Atlantic (>7%), South Indian (>9%), and South Pacific Oceans (>15%)]. This result suggests that the 350-K LC1 RWB on the tropopause preferentially occurs over the midoceans, which is consistent with the results in Postel and Hitchman (1999, see their Fig. 5b). Three similar regions with high frequency of RWB occurrences are also noticed by Berrisford et al. (2007, see their Fig. 8).

On the 322-K isentropic surface, the PV streamers are detected along the climatological jet core. The LC1-like PV streamers are almost absent (<1%), and the activity of the LC2-like PV streamers is also relatively weak (<4%) in the South Atlantic and the South Indian Ocean where the zonal wind is strong. Both types of PV streamers predominantly occur at weak zonal wind regions: the south Pacific sectors, namely, downstream of the SH storm track (see Fig. 6c of Berrisford et al. 2007). The regions where the occurrences of the LC1-like PV streamer are relatively frequent (>2%) are more locally confined, stretching from the date line to the eastern South Pacific. The LC2-like PV streamers are prevalent along a whole zonal ring. The frequency maxima (>5%) are situated downstream of the MLJ over the western South Pacific. It is noticeable that the maximum of the LC1-like PV streamers is located in a farther downstream region relative to that of the LC2-like PV streamers. This result may reflect the influences of near-surface baroclinicity on the types of RWB. Orlanski (2003) argued that the intensity of the near-surface baroclinicity has a profound influence on the RWB. An intense (weak) baroclinicity favors the baroclinic waves breaking in a cyclonic (anticyclonic) manner. Thus, the climatological distributions of the 322-K PV streamer are consistent with Orlanski’s argument that the LC1 RWB tends to occur in a farther downstream region where the baroclinicity is weaker.

On the 310-K isentropic surface, the PV streamers are detected at the poleward side of the climatological MLJ. In general, the 310-K PV streamers are much more vigorous, encircling Antarctica with a good zonal symmetry. The frequency of the LC1-like PV streamer is the highest (>9%) from the eastern South Pacific to the South Indian Ocean but is the lowest (<7%) in the western South Pacific. The occurrence of the LC2-like PV streamers is very frequent (>10%) along the whole zonal ring, especially over the South Indian Ocean (>15%). If combining the climatological distribution of the LC1 and LC2 310-K PV streamers, one would see that the PV streamers predominantly occur in the eastern South Pacific, South Atlantic, and South Indian Oceans. This is consistent with the summertime RWB climatology shown by Berrisford et al. (2007, see their Fig. 8) and with the summer polar RWB maxima shown by Hitchman and Huesmann (2007, see their Fig. 3).

b. JJA

In the austral winter, the PV streamers are identified on six isentropic surfaces, with the results shown in Fig. 5.

On the 340-K isentropic surface, from the eastern South Indian Ocean to the central South Pacific Ocean (the STJ sector), the intersection of the isentropic surface with the dynamical tropopause is located at the central axis of the climatological STJ. In this sector, both types of 340-K PV streamers are rarely observed (<1%). From the eastern South Pacific Ocean to the western

5 The eastern part of the PV streamer near Australia on 5 August 1996 is not identified as an LC2 streamer because its spatial scale is too small.
FIG. 4. DJF-mean frequency (%) of the LC1 and LC2 PV streamers (shaded and thin contours) and the climatological-mean zonal wind speed (bold contours, 20 and 30 m s$^{-1}$) on the 350-, 322-, and 310-K isentropic surfaces. The interval of the thin contour is 2%.
Fig. 5. JJA-mean frequency (%) of the LC1 and LC2 PV streamers (shaded and thin contours), and the climatological zonal wind speed (bold contours, 20, 30, 40, and 50 m s$^{-1}$) on the 340-, 325-, 320-, 315-, 310-, and 303-K isentropic surfaces. The interval of the thin contour is 2%.
FIG. 5. (Continued)
South Indian Ocean (the MLJ sector), the LC1-like PV streamers occur quite frequently but the LC2-like PV streamers seem absent. Although the intersection of the 325-K isentropic surface is located very close to the 340-K intersection with a slight southward displacement, the occurrence frequency of the PV streamers has dramatic changes. In addition to the MLJ sector, there are frequent occurrences of the LC1-like PV streamers (>5%) over the regions from the eastern South Indian Ocean (the DU region) to the Australian and New Zealand region (the split-jet region), whereas the 340-K PV streamers are seldom found in those regions. Moreover, the LC2-like PV streamers can be seen over the Australian and New Zealand region, at the poleward side of the STJ. These differences between the spatial distributions of the 325- and 340-K PV streamers suggest that the “real world” setting the occurrences of the RWB are very sensitive to the variation of the basic flow in which the Rossby waves are embedded.

On the lower-isentropic surfaces (320 and 315 K), the overall spatial patterns of the frequency of occurrence of the PV streamers are similar to the results of the 325 K. The exception is that, from the 325- to 315-K isentropic surfaces, the occurrences of both types of PV streamers become more frequent and the frequency maximum of the LC1 (LC2)-like PV streamers gradually shifts to the southeast (south). As shown in Fig. 2, the two regions with a double-jet setting (the DU region and split-jet region) are well covered by the intersections of 325, 320, and 315 K. Hence, the occurrence frequency of the PV streamers on these three isentropic surfaces may provide some information about the relationship between the multiple-jet environments and different classes of RWB. In the DU region, we find that the PV streamers are predominated by the frequent occurrence of the LC1-like PV streamers. In the NH, the zonal wind situation over the eastern North Atlantic Ocean resembles the DU configuration described here. Martius et al. (2007) also showed that the occurrence of the NH LC1-like PV streamers over that region is very frequent (see their Fig. 5, 330- and 340-K results). In the split-jet region, the occurrence of the LC1-like PV streamers is still dominated by the LC1, while the occurrence of the LC2-like PV streamers is frequent as well (see the 315-K results). This result is consistent with the point made by Berrisford et al. (2007), who argued that the wave breaking that occurs in the midlatitude over the New Zealand–west Pacific region, between the equatorward side of the MLJ and poleward side of the STJ, could be described as a mixture between cyclonic and anticyclonic types. From the results of the spatial distribution of 325-, 320-, and 315-K PV streamers, the present study has shown that the maximum of the LC2-like PV streamers is basically confined within the split-jet region. This is because in the MLJ sector the intersections of the 325-, 320-, and 315-K isentropic surfaces are situated at the equatorward side or in the core of the climatological MLJ, where the LC2-like PV streamers are seldom detected.

The intersections of 310 and 303 K are far away from the STJ during the austral winter. Hence, the ambient flow configurations of these two intersections are dominated by a single-jet setting, which is similar to that of the 322 and 310 K in the austral summer. Thus, it is logical to see that the winter climatological distributions of the 310- and 303-K PV streamers resemble the summer results for the 322- and 310-K isentropic surfaces to a certain degree. On the 310-K isentropic surface, the occurrences of the LC1-like PV streamers are frequent (with the maximum values exceeding 8%) over the whole South Pacific sectors (~150°E–60°W), but they are relatively infrequent (<4%) in the South Atlantic and the South Indian Ocean sectors (~20°W–60°E) where the zonal wind speed is large. For the LC2-like PV streamer, the spatial distribution of the frequency of occurrence is generally vigorous (>4%) with a better zonal symmetry. Both types of 303-K PV streamers occur most frequently in the South Atlantic and the South Indian Ocean sectors but relatively less frequently in the South Pacific sector. The occurrence frequency of the LC1-like PV streamers has a longitudinally confined maximum region (>7%) located in the downstream of South America. In contrast, the occurrence frequency of the LC2-like PV streamers has an elongated maximum region (>9%) extending from the eastern South Atlantic Ocean to the South Indian Ocean along the poleward side of the MLJ. From Figs. 4 and 5, we note that the LC1-like PV streamers are frequently detected at the poleward side of the climatological MLJ in a broad longitudinal range in DJF months, whereas, in JJA months, the occurrence frequency of the LC1-like PV streamers has a rather localized maximum at the entrance of the MLJ. The authors consider that this difference may relate to the seasonal variations of the near-surface baroclinicity at the edge of the Antarctic continent. In DJF months, the near-surface baroclinicity at the edge of the Antarctic continent is weak, whereas in JJA months there is a strong baroclinic zone collocated with the edge of the Antarctic continent (see Fig. 1 of Simmonds and Lim 2009). The strong baroclinic zone would make the emergence of the LC1 RWB difficult over there. Thus, we see that the maximum of the LC1-like PV streamers at the poleward side of the climatological MLJ in the JJA months is localized and do not extend farther from the entrance to the exit of the MLJ.
4. Discussion and conclusions

In this study, the climatological distribution of the LC1 and LC2 RWB in the SH is accessed by investigating the observational occurrence frequency of the LC1- and LC2-like stratospheric PV streamers identified by an objective algorithm along the intersection between the dynamical tropopause (≈2-PVU isosurface) and several isentropic surfaces in the austral summer (DJF: 350, 322, and 310 K) and winter (JJA: 340, 325, 320, 315, 310, and 303 K). Our results indicate that the frequency of both PV streamer classes in the SH has substantial variations with respect to longitude and latitude. This is because the average intersections of different isentropic surfaces with the dynamical tropopause are located in different background flow conditions. The common characteristics of the climatological distribution of the LC1- and LC2-like PV streamers in the SH can be summarized as follows:

1) On the equatorward flank of the climatological MLJ, the LC1-like PV streamers are frequently found over the central oceanic regions, whereas the LC2-like PV streamers are almost absent. On the poleward flank of the climatological MLJ, both types of PV streamers are frequently observed and the LC2-like PV streamers predominate. The results showing that the PV streamers are respectively dominated by LC1- and LC2-like PV streamers at the equatorward and poleward side of the climatological MLJ is consistent with many previous theoretical studies (Simmons and Hoskins 1978, 1980; Thorncroft et al. 1993; Hartmann and Zuercher 1998), reflecting the influences of the barotropic meridional shear of background flow on the baroclinic wave life cycles. It is well known that the LC1 (LC2) RWB events transport eddy momentum fluxes poleward (equatorward). Thus, this RWB distribution characteristic is also consistent with the eddy-driven jet viewpoint that, for driving and maintaining the MLJ against friction dissipation, the eddy momentum flux must be converged in the middle of the jet. As suggested by Postel and Hitchman (1999), for the frequent occurrences of the LC1-like PV streamers at the equatorward side of the climatological MLJ, the tropospheric and stratospheric PV is rapidly advected by the flows of the summer subtropical highs in an anticyclonic manner, which is also propitious to the formation of the LC1-like PV streamers (see Fig. 9 in Postel and Hitchman 1999). The SH subtropical highs are generally located over the oceans between 20° and 40°S of latitude. Thus, this argument may explain why the maxima of the LC1-like PV streamers at the equatorward side of the climatological MLJ are located in the central oceanic regions.

2) The regions where the occurrences of the PV streamers are frequent overlap the weak zonal wind regions. In other words, in the strong zonal wind regions (jet core), the occurrences of both types of PV streamers are relatively infrequent. The strong (weak) zonal wind corresponds to sharp (gentle) PV gradients. Therefore, the fact that the occurrences of the PV streamers are relatively infrequent (frequent) over the strong (weak) zonal wind regions is consistent with the argument that weak PV gradients have less capability to support the propagation of the RWB and thus favor the wave breaking, that is, the enhanced PV gradient at the jet center might tend to inhibit wave breaking (Hitchman and Huesmann 2007). According to the thermal wind relationship, the regions with strong zonal winds in the upper troposphere also generally correspond to strong baroclinic regions (e.g., the MLJ overlaps well with the main baroclinic regions in the SH); therefore, the infrequent PV streamers in the strong zonal wind regions could also be due to the fact that baroclinic waves are forming in the strong baroclinic regions but do not have enough time to amplify (see also Gerber and Vallis 2009). Moreover, it should also be noted that the occurrence frequency of the PV streamers at a certain gridpoint depends not only on the actual number of individual PV streamers occurring at that gridpoint but also the duration of the streamers staying at that gridpoint. Therefore, owing to the quicker (slower) advection in the strong (weak) zonal wind regions, the decreased (increased) frequency of occurrence of the PV streamers in the strong (weak) zonal wind regions may, additionally, be caused by a larger (smaller) phase speed there.

3) In the double-jet setting regions, the LC1-like PV streamers are frequently found both in the DU and the split-jet regions, while the occurrence of the LC2-like PV streamers is frequent in the split-jet region but is rather infrequent in the DU region.6 For the DU region, the STJ located in the downstream and equatorward of the MLJ may act like a waveguide (Hoskins and Ambrizio 1993) affecting wave propagation. The upstream baroclinic wave train propagating along the upstream MLJ splits into two branches, with a stronger tendency to propagate

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6 It should be noted that the DU region or the split-jet region denotes a double-jet setting region that is located in the midlatitude band, and the regions within the DU or the split-jet longitude in the high-latitude band are not the DU and the split-jet region.
toward the subtropical latitudes than toward the higher latitudes (see Fig. 10 and 11 in Chang 1999). Hence, the baroclinic waves have a clear equatorward propagation characteristic, which favors the formation of the LC1-like PV streamers over the DU region.

In contrast to the almost absence of the LC2-like PV streamers in the DU region, the wave breaking that occurs in the split-jet region is a mixture between cyclonic and anticyclonic types. Undoubtedly, a very slow zonal wind speed (gentle PV gradient and small phase speed) in the split-jet region favors the frequent detection of the both types of the PV streamers. Besides that, the authors consider that the LC1-like PV streamers are frequently found in the split-jet region because of the following: 1) the split-jet region is located downstream of the DU region where the LC1-like PV streamers are frequently found, so there are many LC1-like PV streamers detected in the split-jet regions, in fact, it is advected downstream from the DU region; and 2) the baroclinicity of the split-jet regions is very weak, which also favors the emergence of the LC1-like PV streamers (for the baroclinicity distribution of the SH readers can refer to Fig. 1 in Simmonds and Lim 2009). Unlike the DU region, there are some factors associated with the background flow of the split-jet regions also favoring the emergence of the LC2-like PV streamers; 1) the strong STJ paralleled with the MLJ, which tends to meridionally trap the baroclinic waves (Lee and Kim 2003), so that the radiation of the baroclinic waves in the meridional direction is weak; and 2) the presence of the strong STJ causes the primary region of baroclinic waves growth migrating equatorward (Lee and Kim 2003). Rivière (2009) had proved that when a baroclinic wave develops and propagates at lower (higher) latitudes, it tends to break in the LC2 (LC1) manner. It should be noted that, although there are some factors that favor the emergence of the LC2-like PV streamers in the split-jet region, the occurrence frequency of the LC1-like PV streamers is higher than that of the LC2-like PV streamers, which means that those factors favoring the emergence of the LC1- and LC2-like PV streamers are competing between each other, and the factors favoring the LC1-like PV streamers are dominant.

In this study, the PV streamers are preferentially detected on the dynamic tropopause because the RWB is considered as the final stage of the baroclinic wave life cycles and its structures are most evident in the upper troposphere. Therefore, the RWB events on other surfaces cannot be visible in the present analysis. In this study, the identification of the LC1 and LC2 RWB is completely based on the LC1- and LC2-like PV streamer structures. Hence, there are certainly some shortcomings that exist. First, a LC1 (LC2) RWB event is always associated with a LC1 (LC2)-like PV streamer. However, in observations, the structures of the PV streamer are highly variable, an LC1 (LC2)-like PV streamer does not definitely represent the LC1 (LC2) RWB event. For example, the LC1-like PV streamers are frequently detected at the poleward side of the climatological MLJ. Because the jet is displaced poleward when the LC1 RWB events occur, this can partly explain why we can find the LC1-like PV streamers at the poleward side of the climatological MLJ. However, at least, a part of those LC1-like PV streamers detected at the poleward side of the climatological MLJ cannot be directly considered as the LC1 RWB. The LC1 RWB is always associated with a rapid decrease of eddy-kinetic energy (EKE, see Fig. 4 of Thorncroft et al. 1993), which results from the horizontal wave propagation out of the jet (up-gradient eddy momentum fluxes into the jet). Because the shape of the PV contours of the LC1 RWB clearly indicates an equatorward wave propagation, if the LC1-like PV streamers detected on the poleward flank of the climatological jet represent the LC1 RWB then those LC1 RWB on the poleward side of the climatological jet would be associated with an increase of EKE through the barotropic conversion term because the waves propagate into the jet. This contradicts with the conclusion that the LC1 RWB is associated with a rapid decrease of EKE. Thus, they must represent something other than the LC1 RWB. For example, they may often relate to the omega-shape blocking. Second, in some cases, one PV streamer has the LC1 and LC2 RWB features simultaneously (e.g., see Fig. 3). So an LC1- and an LC2-like PV streamer can be simultaneously identified on the same PV streamer by our PV streamer detection approach. This seems unreasonable because, in an ideal experiment of baroclinic wave life cycles, an individual PV streamer is always associated with either an LC1 or an LC2 cyclone (e.g., Thorncroft et al. 1993). Therefore, strictly speaking, the climatological distribution of the LC1- and LC2-like PV streamers presented in this study only approximates that of the real LC1 and LC2 RWB.

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