The Climatological Rossby Wave Source over the STCZs in the Summer Northern Hemisphere

Riyu LU
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

and

Baek-Jo KIM
Meteorological Research Institute, Korea Meteorological Administration, Seoul, Korea

(Manuscript received 11 December 2002, in final form 26 November 2003)

Abstract

Using the twice-daily data for the 10-year period from 1989 to 1998, from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis, the authors analyze the climatological Rossby wave sources at 200 hPa in summer, focusing on the upper-tropospheric circulation related to the subtropical convergence zones (STCZs) in the Northern Hemisphere, namely, the North Pacific convergence zone (NPCZ, including the Meiyu/Baiu front) and the North Atlantic convergence zone.

In the June-July-August (JJA) period, a Rossby wave sink clearly appears along the upper-tropospheric westerly jet streams over East Asia and the extratropical North Pacific, but is very weak in the extratropical North Atlantic. For the JJA mean, or in early summer (June), the Rossby wave sink over East Asia, and the extratropical North Pacific, is much stronger than that in the tropical western North Pacific. The latter sink, however, becomes stronger in late summer (August), corresponding to the enhancement and poleward shift of the atmospheric convection, and becomes comparable with the former sink.

The components of the Rossby wave source, namely, vortex stretching and advection of absolute vorticity by divergent flow, are also examined and used to judge the roles of tropical and extratropical heatings. Despite the integrated appearance of the sink along the NPCZ, this sink results dominantly from the advection of absolute vorticity by divergent flow in East Asia, and the western Pacific, and from vortex stretching over the mid-Pacific. These results reveal that the tropical heating is responsible for the maintenance of upper-tropospheric circulation in East Asia, and the extratropical western North Pacific, through the advection of absolute vorticity by divergent flow, while the diabatic heating in the NPCZ plays a dominant role in maintaining the upper-tropospheric circulation over the mid-Pacific.

1. Introduction

The subtropical convergence zones (STCZs) are unique and are characterized by the intermediate features between tropical and midlatitude rainfall systems (Ninomiya 1984; Kodama 1992). They are oriented southwest (northwest) to northeast (southeast) from the tropics into the middle latitudes in the Northern (Southern) Hemisphere. The STCZs are accompanied by the upper and lower tropospheric circulations in the subtropics (Vincent 1982; Tao and Chen 1987; Kodama 1992, 1993; Yamazaki and Chen 1993; and others).
The upper-tropospheric westerly jet streams are a crucial factor for the STCZs, although the lower tropospheric flows are also important and transport water vapour from the tropics into the STCZs (Ninomiya 1984; Kodama 1992, 1993; Yamazaki and Chen 1993). Kodama (1993) showed that the STCZs appear where the following two conditions are satisfied: (1) there is a strong upper-tropospheric jet stream in the subtropics, and (2) the poleward lower tropospheric flows prevail in the western peripheries of the subtropical highs. The STCZs, in turn, as a thermal heating source, may affect the upper-tropospheric subtropical jets and lower tropospheric subtropical anticyclones (Ninomiya 1980; Yamazaki and Chen 1993; Kodama 1999).

There have been several studies on the mechanisms responsible for the production of the circulation associated with the STCZs. Hoskins and Rodwell (1995) showed that a global, hydrostatic, primitive equation model, forced with a prescribed diabatic heating and with no mountains, is able to reproduce a realistic summer upper-tropospheric circulation and an approximate subtropical high in the lower troposphere. They suggested that the existence and intensity of the summer subtropical anticyclones in the oceans are directly related to the tropical monsoon heatings on the continents. Chen et al. (2001) obtained realistic features of the lower tropospheric subtropical anticyclones, and the upper-tropospheric mid-oceanic troughs, by a linear quasigeostrophic model forced by realistic heating fields, and emphasized the role of the large-scale heat sources over Asia. These studies implied the importance of the role of the tropical heating, although the tropical heating and subtropical heating were not separated. Some other studies (Figueroa et al. 1995; Ose 1998; Kodama 1999) suggested that the tropical heatings, especially the tropical monsoon heatings, are responsible for the formation of the STCZs.

On the other hand, Kodama (1999) investigated the role of atmospheric heating sources in the subtropics, as well as in the tropics, by an aqua-planet general circulation model (GCM), and suggested that the diabatic heating in the STCZs is helpful for maintaining the STCZs. Using a model similar to that of Hoskins and Rodwell (1995), Ose (1998) also showed that including the subtropical heat sources associated with the Baiu rainfall, produces a more realistic feature of circulation in the subtropics. Additionally, some other studies emphasized the role of the extratropical heating (Wang and Ting 1999; Enomoto et al. 2003), although these studies did not discuss directly the STCZs.

The Rossby wave source and its components are to be examined in this study, for the purpose of better understanding the mechanisms responsible for the maintenance of circulation related to the STCZs, and for the tropical-extratropical interactions. Sardeshmukh and Hoskins (1988) demonstrated that the Rossby wave source can be very different from the simple vortex-stretching source, due to the advection of absolute vorticity by divergent flow. The divergent flow essentially results from broad-scale tropical heatings, and thus the extratropical Rossby wave source may be partly related to the tropical heatings.

A brief description of the subtropical rainfall and circulation is given in section 2. In section 3, a vorticity budget analysis is performed at the level of 200 hPa, focusing on the Rossby wave source and its components. 200 hPa, as an equivalent-barotropic level, is appropriate for studying the tropical-extratropical interactions with one-level vorticity budget analysis. The seasonal variation of the Rossby wave source is examined in section 4. Finally, a summary is presented in section 5.

2. A brief description of the upper-tropospheric circulation

Data used in this study are derived from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al. 1996). The dataset has a 2.5 degrees by 2.5 degrees horizontal resolution. The data used in the calculation of this study are the daily 00 and 12 GMT NCEP-NCAR reanalysis data at 200 hPa for the 10-year period from 1989 to 1998.

In summer, the inter-tropical convergence zones (ITCZs) move into the Northern Hemisphere, and strong rainfall appears in the ITCZs (Fig. 1). Connected with the ITCZs, two rainfall bands extend northeastwards in the North Pacific and North Atlantic, respectively, that is, the subtropical convergence zones in
the North Pacific (hereafter referred to as NPCZ) and North Atlantic. The Meiyu/Baiu rainfall band is considered as the west extent of the NPCZ. The North Atlantic convergence zone is also discussed in this study, for the purpose of providing a comparative object of the NPCZ. The precipitation data used for Fig. 1 are based on gauge observations and satellite-estimates (Xie and Arkin 1997).

These rainfall distributions are consistent with those of the upper-tropospheric divergence in the tropics, and over the extratropical North Pacific and North Atlantic. A careful comparison shows that the upper-tropospheric divergence occurs slightly poleward of the rainfall in the extratropical North Pacific and North Atlantic. Over the North Pacific and North Atlantic, the good agreement between the upper-tropospheric divergence and rainfall suggests that the upper-tropospheric divergence results from diabatic heating to a large extent, like the situation in the tropics. Therefore, it is reasonable to link the STCZs to the upper-tropospheric vortex squeezing.

At 200 hPa, the westerly jets are in the shape of a southwest-northeast tilt over the oceans, while they are basically zonally oriented over continents (Fig. 2a). The upper-tropospheric jets are located poleward of the STCZs, as mentioned in previous studies (e.g., Kodama 1992; Yamazaki and Chen 1993).

The JJA mean relative vorticity (Fig. 2b) is closely related to the upper-tropospheric westerly jet streams. Positive and negative vorticities appear poleward and equatorward of the jet cores, respectively, because the relative vorticity is dominantly determined by the meridional gradient of zonal wind, rather than the zonal gradient of meridional wind.

The absolute vorticity at 200 hPa (Fig. 3a) shows a great poleward gradient along the upper-tropospheric westerly jet streams, particularly over northern China, Korea and Japan, mostly due to the strong poleward gradient of relative vorticity along the jet streams (Fig. 2b). Figure 3b shows the velocity potential and divergent flow at 200 hPa. Corresponding to the strong heating over South Asia, and the tropical western North Pacific (Fig. 1), strong negative velocity potential occurs over the eastern Eurasian continent and the western Pacific. The positive velocity potential appears basically over the subtropical Southern Hemisphere (not included in Fig. 3b). The divergent flow radiates from South Asia and the tropical western North Pacific, and extends into the Eurasian continent and most parts of the Pacific. There is a minor divergent flow centered over tropical North America. Over East Asia and the western North Pacific, the southerly divergent flow concurs with the great poleward gradient of absolute vorticity, indicat-
ing strongly negative advection of the absolute vorticity by divergent flow along the upper-tropospheric westerly jet.

3. The climatological Rossby wave source at 200 hPa

At 200 hPa, in a sufficiently long time average, such as the summer mean in this study, the vorticity tendency is negligibly small. The vertical advection and twisting terms are also very small and negligible (Sardeshmukh and Hoskins 1985; Mo and Rasmusson 1993). After neglecting these terms, the vorticity equation may be approximated as

\[ \mathbf{V} \cdot \nabla (f + \zeta) = S, \]

\[ S = -\mathbf{V} \cdot (f + \zeta) \mathbf{V}_z = -(f + \zeta) D - \zeta D' \]

\[ - \mathbf{V}_x \cdot \nabla (f + \zeta) - \mathbf{V}_x \cdot \mathbf{V}_z, \]

where the overbar denotes multiyear mean, and the prime indicates deviation from the mean. \( f \) is the Coriolis parameter, and \( \zeta \) and \( D \) are relative vorticity and divergence, respectively. \( \mathbf{V} = (u, v) \) is the horizontal wind vector, and \( \mathbf{V}_r \) and \( \mathbf{V}_d \) are the rotational and divergent components of the horizontal wind, respectively. \( S \) is the Rossby wave source. The rota-
tional and divergent components of the horizontal wind were calculated by inverting the Laplacian operator in spherical harmonic space with truncation R30. All figures in the present paper are for multiyear seasonal (this section) or monthly (the following section) mean.

The balance equation states that the time-averaged vorticity field can be viewed as being maintained primarily by a balance between vorticity sources/sinks, arising from the divergent component of flow, and the redistribution of vorticity by the rotational component of flow.

The vortex stretching term \(- (f + \zeta) D - \zeta D'\) is negative over the tropical monsoon regions and along the NPCZ and North Atlantic convergence zone, and is positive over the oceanic 'deserts', that is, the eastern extents of the North Pacific and Atlantic, where rainfall is extremely light and strong descent flows occur (Fig. 4a). The vortex squeezing over the North Pacific concurs with the core of the upper-tropospheric jet.

The advection of absolute vorticity by divergent flow \(- \nabla_x \cdot \nabla (f + \zeta) - \nabla^\prime_x \cdot \nabla^\prime \zeta\) is signifi-

---

**Fig. 3.** Climatological JJA mean absolute vorticity (a) and velocity potential and divergent flow (b) at 200 hPa. Units in $1 \times 10^{-5} \text{s}^{-1}$ (a) and in $1 \times 10^{-6} \text{m}^2 \text{s}^{-1}$ for velocity potential and ms$^{-1}$ for divergent flow (b). Contour interval is 3, and dashed lines indicate negative values in (b).
significantly negative along the upper-tropospheric westerly jet over northern China, Korea and Japan (Fig. 4b), due to the southerly divergent flow, and the maximal poleward gradient of absolute vorticity over there (Fig. 3). Positive advection occurs over the North Atlantic convergence zone, corresponding to the northerly divergent flow there, and counteracts with the weak vortex squeezing.

Figure 5a shows the vortex stretching, contributed by transient eddies and year-to-year variations, \((-\nabla \cdot \mathbf{V} - \zeta \nabla f)\). Interestingly, there are well organized positive values in the vicinity of the East Asian jet and North American jet, although this term is small. Note that the contour interval is \(2 \times 10^{-11} \text{ s}^{-2}\) in Fig. 5, much smaller than that in Fig. 4. The advection of vorticity by transient divergent flow \((-\nabla \cdot \mathbf{V})\), Fig. 5b) shows a fairly similar distribution with the vortex stretching contributed by transient eddies in the vicinity of the East Asian jet and North American jet, but with opposite signs. Thus, transient eddies totally make very little contribution to the Rossby wave source.

Figure 6a shows the Rossby wave source, that is, the sum of stretching (Fig. 4a) and advection of absolute vorticity by divergent flow (Fig. 4b). There is a considerable sink along the upper-tropospheric westerly jet stream over China, Korea, Japan and the mid-Pacific. This
sink is much stronger than the vortex squeezing in East Asia and the western Pacific (Fig. 4a), indicating the extreme importance of the advection of absolute vorticity by divergent flow in these regions. Comparing Fig. 6a and Fig. 4 show that the Rossby wave sink results dominantly from the negative advection of absolute vorticity by divergent flow in East Asia and the extratropical western Pacific, and from the vortex squeezing over the central North Pacific. There is also a Rossby wave sink in South Asia and the tropical western Pacific. This sink is mainly due to the vortex squeezing (Fig. 4a).

The heating over South Asia, and the tropical western North Pacific, may play a crucial role in maintaining the extratropical circulation over East Asia and the western Pacific. It has been shown in Fig. 4 that the sink over East Asia and the western Pacific results dominantly from the advection of absolute vorticity by divergent flow. Additionally, the southerly divergent flow over East Asia and the western Pacific, which is a crucial factor determining, at least qualitatively, the advection of absolute vorticity by divergent flow, is related to the heating over South Asia and the tropical western North Pacific (Fig. 3b). Thus, the tropical heating is responsible for the Rossby wave sink in East Asia and the extratropical western North Pacific. Actually, many previous studies suggested the important role of heating forcing over South Asia and the tropical western North

---

**Fig. 5.** Same as Fig. 4, but for the contribution from the transient eddy and year-to-year variation. Contour interval is 2.
Pacific, in maintaining the circulation in East Asia and the extratropical western North Pacific (Kato 1989; Ose 1998).

The Rossby wave sources/sinks are well balanced by the redistribution of vorticity by the rotational component of flow ($\nabla_{\psi} \cdot \nabla (f + \zeta)$, Fig. 6b). The negative values of the redistribution of vorticity by the rotational component of flow, indicate that the rotational flow cuts through the contour lines of absolute vorticity equatorward in East Asia, and equatorward and eastward in the North Pacific (not shown).

4. Seasonal variation of the Rossby wave source

The Meiyu/Baiu front is an early summer phenomenon, and becomes weak in late summer. This can be illustrated clearly by Fig. 7. In this section, the summer period is divided into early summer and late summer, which are represented by June and August, respectively. In June, there is clearly a belt of heavy rainfall in South China and the North Pacific, oriented in a southwest-northeast direction. In August, the region of heavy rainfall becomes much broader and extends into the midlatitude North Pacific, but the intensity of rainfall is decreased. The rainfall is much enhanced in the tropical western Pacific in August.

In both months, the upper-tropospheric divergence is generally consistent with the rainfall, but exhibits a slight poleward displacement over the North Pacific and North Atlantic. Although the divergence associated with the
NPCZ is decreased in August, there are indeed zones of divergence in East Asia and the mid-latitude North Pacific (Fig. 7b). It is necessary to examine separately the Rossby wave sources in June and August, since averaging over the entire JJA period may obscure the remarkable seasonal evolution over East Asia and the North Pacific. In the North Atlantic, the rainfall and upper-tropospheric divergence, do not exhibit a great change in either intensity or distribution from June to August.

Figure 8 shows the Rossby wave sources in June and August, respectively. The region of the Rossby wave sink in East Asia and the extratropical North Pacific is shifted poleward from June to August, in line with the significant poleward shift of the upper-tropospheric westerly jet. The Rossby wave sink in the tropical North Pacific is also shifted poleward, corresponding to the poleward jump of atmospheric convection.

The intensity of the Rossby wave sink also exhibits a significant change from June to August over the western North Pacific. In June, the Rossby wave sink is strong along the upper-tropospheric westerly jet, but weak in the tropics. The subtropical Rossby wave sink is 2–3 times the tropical one. In August, the sink becomes slightly weaker along the jet, but stronger in the tropics, in comparison with that in June. In August, the Rossby wave sink in the tropical western North Pacific, is comparable to
that in East Asia and the extratropical North Pacific.

The sink decrease from June to August in East Asia and the extratropical western North Pacific results from the weakened poleward gradient of absolute vorticity in August (not shown), corresponding to the weakness of the westerly jet from June to August. The upper-tropospheric northward divergent flow does not change obviously from June to August over East Asia and the extratropical western North Pacific, despite the fact that the convection over the tropical western Pacific is enhanced and shows a more northward shift in August. On the other hand, the sink enhancement from June to August in the tropical western North Pacific, results from the increase of vortex squeezing (not shown), which is related to the dramatically enhanced convection over there (Nakazawa 1992; Ueda and Yasunari 1995, 1996; Wu and Wang 2001).

We analysed the components of the Rossby wave source, and found that the distributions of these components are shifted poleward in East Asia and the North Pacific from June to August (not shown), in line with the poleward shift of the upper-tropospheric westerly jet. Therefore, basically, the results for the JJA situation are also valid for both June and August, if one takes the meridional location of the upper-tropospheric jet or STCZs, rather than the geographical latitudes, as reference.
The Rossby wave sources/sinks are also well balanced by the redistribution of vorticity by the rotational component of flow in these two months. The residual, which is considered in this study as the difference between the Rossby wave sources and the redistribution of vorticity by the rotational flow, tends to appear along the upper-tropospheric westerly jets (Fig. 9).
The spatial scale of the residual is small, suggesting that the present results are within confidence limits.

5. Conclusions and discussion

In this study, we analyze the climatological Rossby wave sources at 200 hPa in boreal summer, particularly in the North Pacific and East Asia, by using the NCEP-NCAR reanalysis data, and illustrate the link between the extratropical upper-tropospheric circulation and the tropical/extratropical heatings.

For the JJA mean, a strong Rossby wave sink occurs along the westerly jet streams over East Asia and the midlatitude North Pacific. There is also a Rossby wave sink in the tropical western North Pacific. The extratropical sink is two times the tropical sink.

Two major components of the Rossby wave sources are also examined. It is found that the Rossby wave sink has different contributory factors over East Asia and the extratropical North Pacific, despite the integrated appearance of the sink. This extratropical sink results dominantly from the advection of absolute vorticity by divergent flow in East Asia and the western Pacific, and from the vortex squeezing over the mid-Pacific. The sink in the tropical western North Pacific is basically due to the vortex squeezing. In the North Atlantic convergence zone, the Rossby wave sink is very weak, due to the counterbalance between the vortex squeezing and positive advection of absolute vorticity by divergent flow.

The Rossby wave sources/sinks exhibit a significant seasonal variation in East Asia and the western North Pacific, corresponding to the extratropical upper-tropospheric westerly jet and rainfall. The Rossby wave sinks are shifted poleward in East Asia and the North Pacific from June to August, in line with the poleward shift of the upper-tropospheric westerly jet. In addition, in August, the sink becomes slightly weaker along the extratropical westerly jet, but stronger in the tropics, in comparison with that in June. Accordingly, the Rossby wave sink in the tropical western North Pacific becomes comparable to that in East Asia and the extratropical North Pacific in August.

The components of the Rossby wave source may be helpful in judging the roles of tropical and extratropical heatings. The strong tropical heating leads directly to circulation change from its local effect on the potential vorticity and indirectly through its effect on remote divergence. Therefore, the negative advection of absolute vorticity by divergent flow over East Asia and the extratropical western Pacific results from the heating over South Asia and tropical western North Pacific. The present results reveal that the tropical heating is responsible for the maintenance of circulation in East Asia and the extratropical western North Pacific, through the advection of absolute vorticity by divergent flow. The diabatic heating in the NPCZ, which is closely related to the vortex squeezing, on the other hand, plays a crucial role in maintaining the upper-tropospheric circulation over the mid-Pacific. Thus, the mechanism for maintaining the circulation related to the Meiyu/Baiu rainfall is different from that over the eastern portion of the NPCZ.

The upper-tropospheric divergence over the North Pacific and North Atlantic may result from the baroclinic nature of the atmosphere, as well as from diabatic heating. This is supported by the slight poleward displacement of divergence in comparison with rainfall. To separate quantitatively the heating over the NPCZ from the tropical heating as well as from the baroclinic effect, however, it is necessary to utilize a multi-level model. The multi-level model should be simple but sophisticated enough to include the thermodynamic budget. The present results, by one-level vorticity budget analysis, provide a base for further quantitative studies.

The present results imply that it is essential to simulate accurately the diabatic heating in South Asia and the tropical western North Pacific, in order to capture well the summer circulation and rainfall in East Asia.

Acknowledgements

The comments of two anonymous reviewers and Dr. Shoshiro Minobe were extremely valuable in revising an earlier version of the manuscript. We thank Drs. B.H. Ren, K.-J. Ha and J.-Y. Moon for their help in calculations, and Prof. J.H. He for discussion. The research work was supported by the National Natural Science Foundation of China under Grant 40075016 and Grant 40221503. It was launched during RL’s visit to the Forecast Research Laboratory.
of the Meteorological Research Institute of the Korea Meteorological Administration (FRL/METRI/KMA) in 2000. His visit was supported by the Brain Pool Program under Grant 991-5-8 founded by the Korea Science and Engineering Foundation, and by the Natural Hazard Prevention Research Project, one of the Critical Technology-21 Programs, funded by the Ministry of Science and Technology of Korea. RL gratefully appreciates the faculty in FRL/Technology-21 Programs, funded by the Ministry of Science and Technology of Korea. His visit was supported by the Brain Pool Program under Grant 991-5-8 founded by the Korea Science and Engineering Foundation, and by the Natural Hazard Prevention Research Project, one of the Critical Technology-21 Programs, funded by the Ministry of Science and Technology of Korea. RL gratefully appreciates the faculty in FRL/METRI for their warm help during his stay.

References


