An air mass with high potential vorticity preceding the formation of the Marcus Convergence Zone

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[1] We examined the convective activity and dynamical field over the subtropical North Pacific by focusing on the relationship between upper cold lows (UCLs) and the formation of the Marcus Convergence Zone (MCZ). In mid-July, we detected a UCL near Marcus Island that was associated with the formation of the MCZ. The convective activity associated with the MCZ followed the UCL, implying that the UCL contributed to the MCZ formation. Analysis of the temporal evolution of the dynamic field revealed that the UCL appeared in a large-scale, high-potential vorticity (PV) air mass migrating from the east. We had already identified the high-PV region near the mid-Pacific trough in late July. It stretched westward and reached Marcus Island in mid-July, suggesting that the UCL in the high-PV air mass over the North Pacific contributed to the formation of the MCZ. **Citation:** Sato, N., K. Sakamoto, and M. Takahashi (2005), An air mass with high potential vorticity preceding the formation of the Marcus Convergence Zone, *Geophys. Res. Lett.*, *32*, L17801, doi:10.1029/2005GL023572.

1. Introduction

[2] *Ueda et al.* [1995] revealed that strong convective activity over the western North Pacific in late July is related to the end of the Baiu (early summer rainy season in Japan). They called this convective activity the convection jump because it appears so suddenly. According to *Ueda and Yasunari* [1996], the warm sea surface temperature (SST) is a necessary condition for inducing this convective activity. However, in their results, the spatial distribution and the abrupt seasonal march of the convection jump did not directly correspond to those of the SST.

[3] *Kodama* [1992] examined the characteristics of the subtropical convergence zone (STCZ). An STCZ is a precipitation system over the subtropical ocean. This convective zone extends northeastward from the warm pool in the Northern Hemisphere and southeastward in the Southern Hemisphere. Especially, according to *Kodama* [1999], strong diabatic heating over the warm pool contributes to the formation and maintenance of the STCZ. N. Sato and M. Takahashi (Characteristics of the midsummer convection zone over the subtropical western North Pacific, submitted to *Monthly Weather Review*, 2005, hereinafter referred to as Sato and Takahashi, submitted manuscript, 2005) investigated the spatial structure of the convection jump and, by analyzing the dynamical fields, demonstrated the common features of the convection jump and the STCZ. Because it was a belt-shaped convergence zone, they called this convective system the Marcus Convergence Zone (MCZ). According to Sato and Takahashi (submitted manuscript, 2005), the convergence zone clearly extends from southwest to northeast in typical years, although the belt-shaped low-T_{BB} is identifiable even in the climatological mean field. The rain gauge data at Marcus Island also confirmed the increased precipitation in late July.

[4] Although Sato and Takahashi (submitted manuscript, 2005) clarified the spatial structure of the convection jump/MCZ, they did not identify the mechanism of the abrupt seasonal march. In general, a high-PV air mass flowing into the low latitudes sometimes contributes to the formation of a convective system. Using satellite data and objectively analyzed data, *Tsuboki and Ogura* [1999] showed that a UCL could trigger convective activity over the subtropical ocean. More recently, *Sakamoto and Takahashi* [2005], using a mesoscale model, examined the mechanism of the UCL formation through the cut-off process for a trough in the mid-latitude westerlies. Furthermore, the analytical results of *Sakamoto and Takahashi* [2004] suggested that the convection jump/MCZ forms in relation to the UCL. In this study, we examined the relationship between the MCZ formation and the UCL, represented by high isentropic potential vorticity (IPV).

2. Methods

[5] We first investigated the horizontal distribution of convective activity using T_{BB} data edited by the Meteorological Research Institute/Japan Meteorological Agency (MRI/JMA). According to *Ueda et al.* [1995] and Sato and Takahashi (submitted manuscript, 2005), the convection

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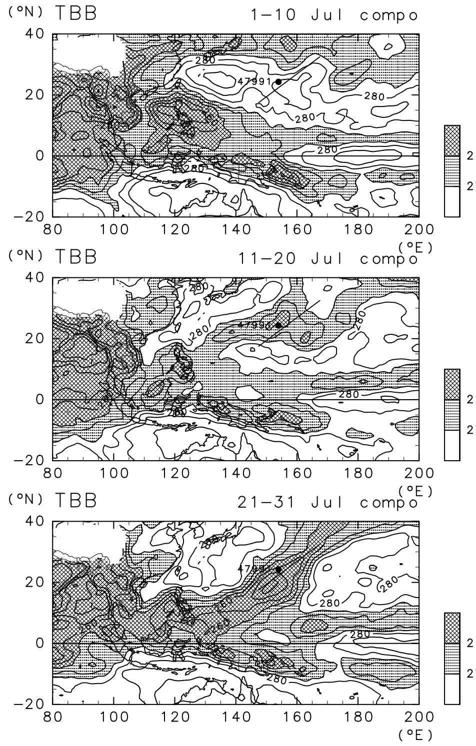

Figure 1. T_{BB} averaged for early July (1–10, upper panel), mid July (11–20, middle panel), and late July (21–31, lower panel) in 1984, 1985, and 1994. The contour interval is 5 K. Values less than 275 K are shaded, and those less than 265 K are hatched. The solid line in each panel indicates the approximate location of the convective region shown in the lower panel. The dot marked "47991" indicates the position of Marcus Island (24°18.0′N, 153°58.0′E).

jump/MCZ forms suddenly in late July. Because of this, we focused on the seasonal march in early July (1 to 10), middle July (11 to 20), and late July (21 to 31). Following Sato and Takahashi (submitted manuscript, 2005), we obtained the spatial resolution data from the T_{BB} data set (1° × 1°), measured every three hours during July of 1984, 1985, and 1994. These were the most typical years, when the low T_{BB} region corresponding to the MCZ in late July was most pronounced. All three of these years were included in the typical years selected by *Ueda and Yasunari* [1996].

[6] We calculated the composed 200 hPa geopotential heights, sea-level pressure (SLP), and 350 K IPV for the same period using objectively analyzed data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) [*Kalnay et al.*, 1996]. We then compared the seasonal march of 200 hPa geopotential height with that of convective activity, focusing on the relationships between the 200 hPa troughs and the low-T_{BB} regions. Our main goal was to confirm the relationship between the MCZ and the UCL, which is often recognized as an IPV maximum near the tropopause [*Tsuboki and Ogura*, 1999]. Therefore, we examined the IPV at 350 K for the 10 to 11-day period from late June (21–30) to late July (21–31). We compared the locations of the UCLs with those of the 200 hPa troughs. Sometimes, the UCL forms near the date line and migrates westward over the North Pacific in summer. We investigated the zonal-time section of 350 K IPV at 30°N.

3. Results

[7] Figure 1 shows the T_{BB} distributions in early, middle, and late July. A clearly defined low-T_{BB} region extends northeastward from the warm pool west of the Philippines in late July (lower panel). Solid lines indicate its approximate location. The low-T_{BB} region can also be detected around Marcus Island in mid-July, but the spatial distribution is different (middle panel). Another convective zone can be detected near the date line. This low-T_{BB} area is also belt-shaped, extending from northeast to southwest. Consequently, there are two T_{BB} minima (at 155°E and 175°E) along the latitude line of 30°N. In early July (upper panel), there is no clearly defined low-T_{BB} region near Marcus Island. However, the belt-shaped low-T_{BB} zone has already appeared near the date line around 30°N. In early July, the T_{BB} is remarkably low around the Philippines. However, this low T_{BB} area becomes indistinct in mid-July (middle panel), especially over the warm pool east of the Philippines. It recovers as a part of the MCZ in late July (lower panel).

[8] Figure 2 depicts the 200 hPa geopotential height for the same periods. Figure 3 shows the corresponding 350 K IPV fields from late June to late July. The dotted line indicates a trough on the northwestern side of the MCZ in late July (lower panel of Figure 2). The SLP is low, corresponding to the low T_{BB} region of the MCZ (not shown). The IPV is high along the trough detected in the geopotential height field (bottom panel of Figure 3). There is a deeper trough near the date line that we call the mid-Pacific trough, and a ridge can be seen on the southeastern side of the MCZ as shown in Figure 2 (lower).

[9] We can see similar troughs and ridge in mid-July (middle panel of Figure 2). However, the trough northwest of Marcus Island is not accompanied by a low SLP (not shown). Although the trough is indistinct in geopotential height field, we identified a clear maximum IPV in mid-July on the northwestern side of the MCZ (third panel of Figure 3). This is accompanied by the low T_{BB} as depicted in Figure 1 (middle). However, the low T_{BB} region is not as clearly identified as that in late July. Although we observed the maximum IPV in mid-July, the trough in the geopotential height field and the convective activity reach their maxima in late July. In other words, the trough in the height field and the convection follows the IPV maximum. Two other IPV maxima occur over the subtropical North Pacific. One is approximately 35°N, 170°E, corresponding to the low-T_{BB} near 175°E in Figure 1 (middle). The other corresponds to the mid-Pacific trough.

[10] In early July, we can already detect the ridge southeast of the MCZ and the trough near the date line (upper panel of Figure 2). However, the trough northwest of the MCZ is still indistinct near Marcus Island. The mid-Pacific trough is more clearly identified in this period (second panel of Figure 3). We can also identify the high-IPV regions northwest of Marcus Island and approximately 35°N, 170°E. Although the high IPV associated with the mid-Pacific can be found in the climatological-mean field

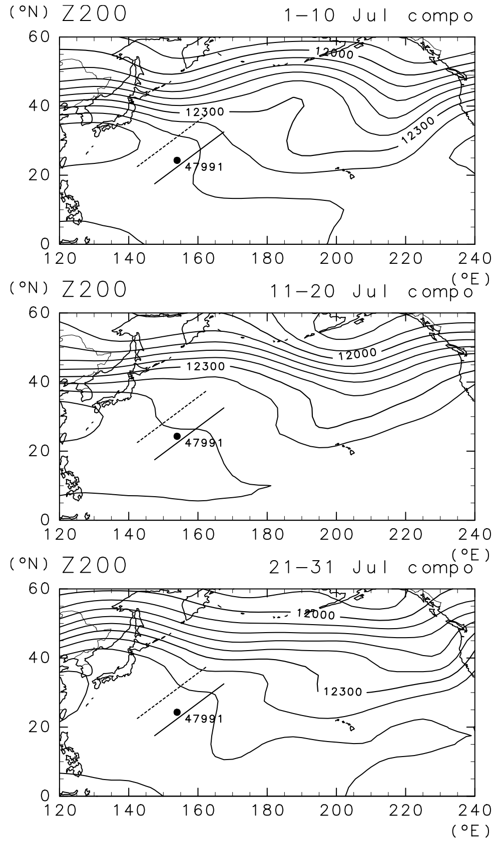

Figure 2. 200 hPa geopotential height averaged for early July (upper panel), mid July (middle panel), and late July (lower panel) for 1984, 1985, and 1994. The contour interval is 30 m. The dotted line in the figure indicates the approximate location of the trough at 200 hPa shown in the lower panel.

(not shown), it is deeper in the selected typical years. There are no significant anomalies in the geopotential height and T_{BB} in late June (not shown). However, the mid-Pacific trough has already deepened (top panel of Figure 3).

[11] Figure 4 depicts the zonal-time section of 350 K IPV at 30°N. There are four IPV maxima at approximately 150°W, 170°W, 170°E, and 150°E. The last three correspond to the IPV maxima detected in the previous paragraphs. Basically, we found all four of the troughs in the IPV section in all three of the typical years, except in 1985 when the trough near 170°E is less distinct (not shown). The first trough appears in late June, and the other maxima form in turn. The last trough at approximately 150°E forms in mid July, corresponding to the IPV maximum shown in the third panel of Figure 3. Essentially, we can identify the large-scale, high-IPV region moving westward from the eastern Pacific to the western Pacific, and it reaches near Marcus Island in mid July.

[12] Although the mid-Pacific trough is also identified in the climatological mean field, we do not detect the trough and the IPV maxima near Marcus Island, and the large-scale westward extension of the high-IPV region, when we perform the same analyses for the climatology (not shown). These dynamic characteristics are observed only in the typical years.

[13] We select three typical years in this study, following Sato and Takahashi (submitted manuscript, 2005). However, IPV maxima or high-IPV regions are also observed in some other typical years [*Sakamoto and Takahashi*, 2004].

4. Discussion

[14] Figure 1 confirms the abrupt formation of the MCZ from mid to late July. Although the convective activity associated with the MCZ is strongest in late July, the spatial maximum of the IPV near Marcus Island is most clearly identified in mid-July, and becomes less defined in late July, as shown in Figure 3. Thus the IPV maximum precedes the peak of the convective activity of the MCZ.

[15] The IPV maximum is not accompanied by dynamic anomalies in the lower troposphere before the convective activity increases in late July. We consider such an IPV maximum near the tropopause to be a UCL. Such UCLs

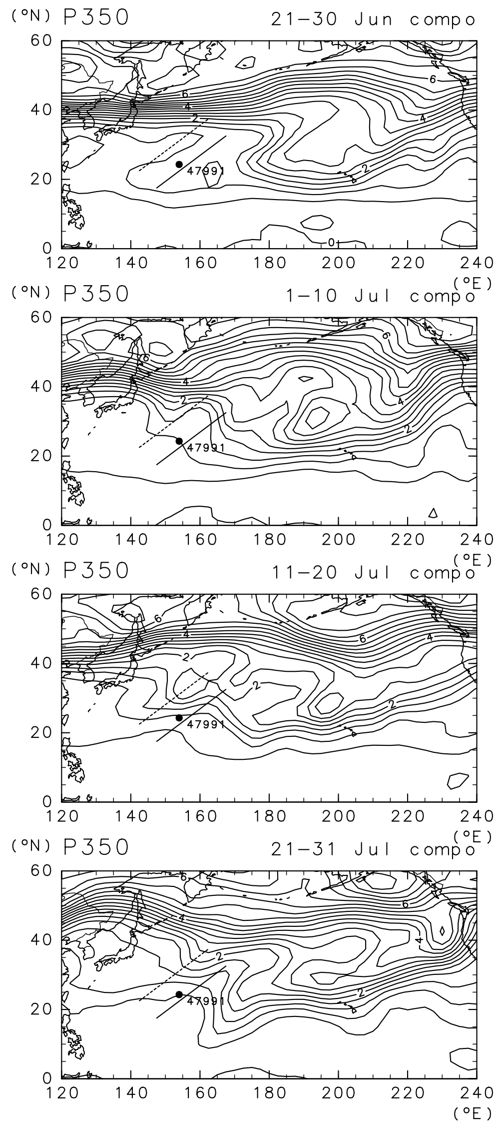

Figure 3. 350 K isentropic potential vorticity averaged for late June (21–30, first panel), early July (1–10, second panel), mid July (11–20, third panel), and late July (21–31, fourth panel) for 1984, 1985, and 1994. The contour interval is 0.5 PVU.

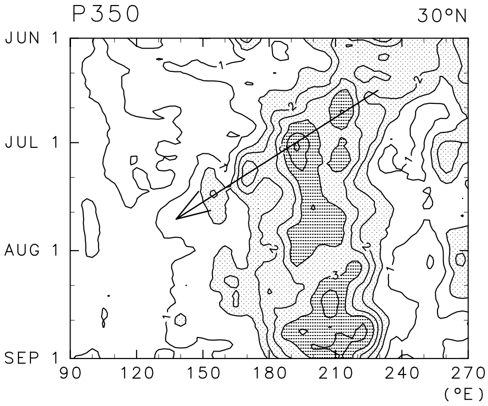

Figure 4. Zonal-time section of 350 K isentropic potential vorticity at 30°N averaged for 1984, 1985, and 1994. The contour interval is 0.5 PVU. Values greater than 1.5 PVU are lightly shaded and those greater than 3 PVU are shaded.

accompany negative temperature anomalies in the upper troposphere, and the atmospheric stability in the middle troposphere under the UCL is low. Generally speaking, such conditions promote convective activity. According to *Tsuboki and Ogura* [1999], a UCL over the summer North Pacific can trigger convective activity especially to the southeast. *Sakamoto and Takahashi* [2004] demonstrated that the convection jump corresponds to a UCL in the northwest, and they suggested that the frontogenesis process plays an important role in forming the convection jump that is related to the UCL. In the upper and middle panels of Figure 1, we observe the relatively strong convective systems southeast of the UCLs. The location of convective activity associated with the MCZ in late July also corresponds to convection accompanied by the UCL northwest of Marcus Island in mid-July. These results imply that the UCL triggers the MCZ.

[16] Figure 4 illustrates the westward migration of a high-IPV air mass with a relatively large spatial scale. In this air mass, the UCLs form at approximately 150°W, 170°W, 170°E, and 150°E, inferring that the large-scale high-IPV air mass contributes to the formation of the UCLs. According to *Sakamoto and Takahashi* [2005], the convective activity around the trough contributes to the cut-off process of the high-IPV air mass, through horizontal divergence in the upper troposphere. According to our results, active convection accompanies the upper troughs northwest of Marcus Island and at approximately 170°E. Convective activity may have formed the wave-like structure in Figure 4, through the mechanism demonstrated in *Sakamoto and Takahashi* [2005]. However, strong convective activity does not accompany the IPV maxima over the middle Pacific, east of the date line. Their cut-offs are probably related to the distorted dynamic field near the mid-Pacific trough. The detailed formation mechanisms of UCLs over the subtropical North Pacific are an interesting topic for future study.

[17] Although there are four UCLs at similar latitudes in the IPV field, only one of them, located at approximately 150°E, can trigger the MCZ. According to Sato and Takahashi (submitted manuscript, 2005), the MCZ has features in common with an STCZ. *Kodama* [1999] revealed that the thermal forcing over the warm pool to its southwest formed the STCZ. Therefore, it is inferred that the warm pool east of the Philippines contributes to the formation of the convergence zone, along with the UCL northwest of Marcus Island.

[18] *Ueda et al.* [1995] and *Ueda and Yasunari* [1996] already revealed that the convection jump/MCZ is closely related to the variability of the East Asian summer monsoon (EASM). Our results imply that the EASM is affected not only by the warm pool near the Philippines but also by dynamic processes in the upper layer over the subtropical North Pacific, through the MCZ formation.

5. Conclusions

[19] We confirmed that the abrupt formation of the MCZ occurs in late July in typical years. Associated with the appearance of the MCZ, we detected a UCL in mid-July near Marcus Island. The UCL is followed by formation of the MCZ. The convective activity associated with the MCZ is induced southeast of the UCL. It thus appears that the UCL contributes to the formation of the MCZ. The UCL appears in a large-scale, high-PV air mass migrating from the east. The high-PV region near the mid-Pacific trough has already been identified in late June in typical years. It moves westward, reaching Marcus Island in mid-July. It is suggested that the UCL formed in the high-PV air mass over the central North Pacific contributes to the formation of the MCZ.

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References

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kodama, Y. (1992), Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ, and the SACZ) part I: Characteristics of subtropical frontal zones, *J. Meteorol. Soc. Jpn.*, *70*, 813–836.

Kodama, Y. (1999), Roles of the atmospheric heat sources in maintaining the subtropical convergence zones: An aqua-planet GCM study, *J. Atmos. Sci.*, *56*, 4032–4049.

Sakamoto, K., and M. Takahashi (2004), The effect of upper cold low on convections over the summer North Pacific, paper presented at Joint AOGS 1st Annual Meeting and 2nd APHW Conference, Asia Oceania Geosci. Soc., Singapore.

Sakamoto, K., and M. Takahashi (2005), Cut off and weakening processes of an upper cold low, *J. Meteorol. Soc. Jpn.*, in press.

Tsuboki, K., and Y. Ogura (1999), A potential vorticity analysis of thunderstorm-related cold lows (in Japanese), *Tenki*, *46*, 453–459.

Ueda, H., and T. Yasunari (1996), Maturing process of the summer monsoon over the western North Pacific—A coupled ocean/atmosphere system, *J. Meteorol. Soc. Jpn.*, *74*, 493–508.

Ueda, H., T. Yasunari, and R. Kawamura (1995), Abrupt seasonal change of large-scale convective activity over the western Pacific in the northern summer, *J. Meteorol. Soc. Jpn.*, *73*, 795–809.

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