The understanding of subseasonal variability of the Asian monsoon anticyclone as shallow water system

*Arata Amemiya[1], Kaoru Sato[1]

1. Graduate School of Earth and Planetary Science, The University of Tokyo

The circulation in the upper troposphere and lower stratosphere (UTLS) over Asia in summer is characterized by the Asian Monsoon Anticyclone (hereafter referred to simply as 'the anticyclone') driven by Monsoonal convective heating. Recently much attention has been paid to the role of the anticyclone on the transport and mixing processes. Despite its importance, the detailed understanding of dynamical and physical processes around the anticyclone is still insufficient. One of the important ongoing discussion is on the mechanism of the subseasonal variability of the anticyclone. An important observed feature is frequent westward propagation with 'bimodal' structure favoring two distinct locations over the east and west Asia. Dynamical understanding of this feature is the main purpose of this study.

Previous studies have tackled this issue from two contrasting perspectives. Some considered the variability of the anticyclone simply as the response to the temporal variability of the tropical convection. Others rather focused on the nonlinear nature of the circulation (Hsu and Plumb, 2000; hereafter referred to as 'HP00'), which lead to the possibility of spontaneous periodic response to a finite amplitude steady forcing. We follow the latter perspective.

First, we revisited HP00 model to examine the validity of their result in a realistic parameter range. The model is a beta-plane shallow water system with linear damping and a localized steady mass source on the subtropics. We confirmed that, with some extension regarding the forcing amplitude range, the vortex shedding is found under the realistic forcing latitude and damping time scale. Moreover, the speed of westward propagation was found approximately 10-20m/s, which is consistent with the real atmosphere.

Next, the validity of shallow water concept is examined using the reanalysis data. We calculated composite of Ertel's potential vorticity (PV), Montgomery streamfunction (M), and thickness (sigma) on isentropic surfaces from ERA-Interim reanalysis for the summer period of 2011-2015, classifying 6-hourly snapshots by the longitudinal location of the anticyclone. On 360 and 365K surfaces, we found excellent consistency regarding the latitudinal structure of the vortex shedding with the shallow water model, in which maximum in M and sigma is located slightly north of low PV anomaly.

The resemblance between the structure of M and sigma implies the validity of the shallow water concept. We further estimate the equivalent depth as the first order coefficient of the linear regression between M and sigma from the reanalysis data. Linear relation between the two quantities is clear not all latitude regions but each of the regions in the north and south of 35N. The estimated depths are approximately 60m and 200~300m in the south and north, respectively.

Last, taking account of the implication above, we performed additional experiments with the shallow water model with the inclusion of the latitudinally dependent mean depth. In a certain range of forcing amplitude, experiments with three times larger equivalent depth on the north produce similar periodic response but with different spatial structure, in which PV and height disturbances favor two center longitude and do not propagate westward beyond(fig. b). This structure is much more realistic than the previous case with homogeneous equivalent depth (fig. a), in terms of the westward propagation and the

'bimodal' behavior.

In summary, **the shallow water model with variable mean depth is found to be capable of reproducing spontaneous westward propagation of the anticyclone with realistic speed and structure**. It is worth emphasizing that this simple model includes neither periodicity in the forcing nor any external longitudinal asymmetry. This suggests that the subseasonal variability of the anticyclone is, at least qualitatively, the intrinsic behavior of the anticyclone itself, but not necessarily due to externally imposed constraints.

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