Equatorial superrotation due to heating and cooling in a 1-1/2 layer shallow water system.

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On Venus, Titan and tidally locked exoplanets, a wind blows at the equator in the direction of their planetary rotation. Such zonal wind is called "superrotation". Showman and Polvani (2010) showed that equatorial superrotation can be generated in the presence of heating and cooling in a 1-1/2 layer shallow-water model that consists of an active upper layer and a deep, quiescent lower layer and includes vertical advection of planetary momentum from the lower layer to the upper layer. They showed a result with a time constant for drag τ_{drag} = 5 days, a radiative time constant τ_{rad} = 5 days, and Earth-like values for other planetary parameters; however parametric dependence of the superrotation was not explored. In this study, we perform parameter experiments in which the drag time constant is varied from 0.1 days to infinity.

In our numerical experiments, equatorial superrotation is generated in all cases, and the equatorial zonal-mean zonal flow $\bar{u}$ becomes faster as the drag time constant increases. The increasing rate of $\bar{u}$ with respect to τ_{drag} is $\bar{u} \propto \tau_{drag}^2$ when $\tau_{drag} \leqq 1$ day; whereas that decreases as τ_{drag} increases when $\tau_{drag} >$ 1 day.

Momentum balance analyses reveal that an eastward acceleration by the meridional flux convergence of the zonal eddy momentum is nearly canceled by a westward acceleration due to forcing to the mass. This means that the acceleration caused by the planetary momentum advection from the lower layer to the upper layer, expressed by the term R, is important for generation and maintenance of the superrotation. If the acceleration does not depend on the drag time constant, then it is expected that $\bar{u} \propto \tau_{drag}^1$ from the balance between the term R and the Rayleigh friction due to the zonal-mean zonal flow. However, our numerical results show that the relationship between the equatorial zonal-mean zonal flow and the drag time constant is not in the simple proportional relationship.

When the drag time constant is short as $\tau_{drag} \leqq 1$ day, the balance between the pressure gradient due to height disturbances and the friction by flow disturbances is dominant. Therefore, the magnitude of the flow disturbances increases in proportional to the drag time constant. In addition, the term R is in proportional to the magnitude of the flow disturbances. Hence, $\bar{u}$ seems to be in proportional to τ_{drag}^2. On the other hand, when the drag time constant is long as $1 < \tau_{drag} \leqq 50$ days, the westerly flow in the heating region ($Q > 0$) grows as τ_{drag} increases but easterly flow there hardly changes (in our numerical results). As a result, the term R decreases and the increasing rate of $\bar{u}$ decreases as the drag time constant increases. Finally, when the drag time constant is very long as $\tau_{drag} > 50$ days, numerical solutions do not achieve steady states and are not similar to the Matsuno-Gill pattern. In addition, an instability occurs, which may affect the generation and maintenance of the equatorial superrotation.

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