A parameter sweep experiment on axisymmetric circulations with an idealized simple model : Hadley circulation and super-rotation

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Held & Hou (1980) studied the dynamics of the Hadley circulation of the Earth with an idealized axisymmetric 2D model, which is known as the Held & Hou (hereafter HH) model. On the other hand, the mechanism of the super-rotation of the Venus was studied by Gierasch (1975). The essence of the Gierasch mechanism is the mean meridional circulation under the large horizontal eddy diffusion. The Gierasch mechanism was studied by Matsuda (1980, hereafter M80) with a Boussinesq fluid model.

Both Held & Hou (1980) and M80 used axisymmetric Boussinesq fluid primitive equations symmetric about the equator with a Newtonian heating/cooling to force the flow field. The difference of them is as follows: the HH model has no horizontal diffusion, while M80 assumes a very large horizontal diffusion. Focusing on above points, we did a parameter sweep experiment of three external non-dimension numbers; the external thermal Rossby number R_T, the vertical Ekman number E_V and the horizontal Ekman number E_H. Then we explored the transition from the HH type Hadley circulation to the solution of the Gierasch mechanism.

The governing equations are solved using the axisymmetric spherical spectral method. The resolution is T85, and 32 layers in the vertical. The initial condition is a rest atmosphere with a constant potential temperature. The time integration is done until the calculation achieves a steady state. In some cases, the calculation did not achieve a steady state because of a symmetric instability. It occurred when E_V and E_H was small and R_T was large.

We introduce three indices to analyze our numerical results. The first is a measure of the intensity of super-rotation S, which is defined as a latitudinal averaged (from equator to pole) zonal wind of the top layer, divided by a planetary radius and a rotation rate. The second is a measure of the direct circulation and defined as a ratio between the latitudinal averaged zonal wind and a latitudinal averaged poleward wind of the top layer, and we call this ratio as gamma. If gamma is small, the direct circulation is more dominant than the gradient wind balance. The last is a measure of rigid rotaion and defined as a ratio of the kinetic energy of rigid rotation of the top layer to the kinetic energy of the zonal wind of the top layer, and we call it as Rg. If Rg is close to unity, the zonal wind field is close to rigid rotation.

We can estimate S when we can assume the gradient wind balance as if R_T less than 1 then S~R_T, while if R_T is greater than 1 then S~${R_T}^{1/2}$. The former means that the geostrophic balance is dominant and the latter means that the cyclostrophic balance is dominant. S of our numerical results show similar values to the estimates when E_V is small and E_H is large.

M80 showed that the direct circulation becomes dominant when E_V is large. In other words, gamma becomes small when E_V is large. Our numerical results show the same property. However, gamma did not become less than 1 in our parameter sweep range.

If we fix R_T and E_V and increase E_H gradually, Rg increases largely when E_H reaches a certain value which depends on R_T and E_V, and gets close to unity. This means that the solution changes from the HH type Hadley circulation to rigid rotation. Using the solution of the HH model, we can estimate the value of E_H when the horizontal diffusion becomes comparable to the vertical diffusion. The estimate gives E_H~E_V*S. When E_H is the estimated value, numerical results show a solution intermediate between the HH type Hadley circulation and rigid rotation, and Rg also shows a large increase.

Considering the circumstances mentioned above, we conclude that the transition from the solution of the HH model to the solution of the Gierasch mechanism is continuous. The position of this transition region depends on E_V and R_T, and it is given by E_H~E_V*S.