On the intensities of the Ferrel cell and TEM circulation – interaction between the lower and the mid-latitude circulations

Contact Person Masaki Satoh
Department of Mechanical Engineering, Saitama Institute of Technology
Okabe, Saitama, 369-02, Japan

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1. Introduction

Although many studies on the interactions between the circulations of the tropics and the extratropics have been done in the context of teleconnection, there has been relatively little concern with the meridional circulation. Recently, as a consequence of studies with axisymmetric models, the Hadley circulation is thought to control the meridional structure of the mid-latitudes and the poleward heat transport through the subtropical jet [1], [2], [3]. In the present study, this framework is extended to reconsider relations between the Hadley cell and the Ferrel cell ; the intensities of the two cells and the statistical properties of the baroclinic waves are investigated with the aid of the angular momentum balance.

2. Intensities of meridional circulations

Because of the angular momentum balance, the maxima of the mass stream functions of the Hadley cell (Ψ_H) and the Ferrel cell (and $-\Psi_F(>0)$) are approximately related by [4]

$$\frac{-\Psi_F}{\Psi_H} = \frac{1}{2}. \tag{1}$$

The Ferrel cell appears as a zonal average of the baroclinic waves and the meridional heat flux exists with it. The Ferrel cell intensity and the meridional heat flux are proportionally related as

$$\overline{v'T'} = B \cdot (-\Psi_F). \tag{2}$$

This relation can be understood as the secondary circulation of the linear theories. The coefficient B should be described by models of the baroclinic waves.

The transformed Eulerian mean (TEM) circulation is more often used as dynamical understanding of the meridional circulations rather than the Eulerian mean circulation, since TEM circulation approximately explains material transports and it directly reflects diabatic process. In the quasi-geostrophic approximation, the intensity of TEM circulation is expressed as

$$\Psi^* = \Psi + \frac{2\pi a \cos\varphi}{g}\left(\frac{\overline{v'\theta'}}{\overline{\theta}_p}\right) \approx (\frac{U}{NH} - 1)(-\Psi_F). \tag{3}$$

The scaling of the heat flux is based on the Eady model.

3. Model and Experiments

To investigate the relation between the Hadley and the Ferrel cells three dimensional experiments have been performed with a Newtonian cooling as radiative forcing. The numerical model is CCSR / NIES AGCM [5]; the resolution is triangular truncations T42 on the sphere and 16 layers in the vertical, and longitudinal periodicity of 60° is assumed. The reference temperature is expressed as

$$T_E = (T_0 - \Delta T|\sin\varphi|^\alpha) \cdot \sigma^{\Gamma R_{gas}/g}, \tag{4}$$

which is valid below the level σ_T, where σ_T corresponds to the tropopause of the reference state, above which the lapse rate is assumed zero. R_{gas} is the gas constant for the dry air and an exponent α is introduced to examine dependency on the latitudinal gradient of the temperature. The parameters of the standard experiment are as follows : $T_0 = 300$ K, $\Delta T = 40$ K, $\tau = 20$ days, $\Gamma = 6.5$ K km^{-1}, $\sigma_T = 0.2$, $\alpha = 2$, viscosity of the atmosphere $\nu = 5$ m^2 s^{-1}, bulk coefficient for the surface stress $C = 0.005$ m s^{-1}, and $2\pi/\Omega = 1$ day. The equilibrium states are defined by the average of 81 – 160 days starting from the isothermal state with no motion.

According to Held and Hou [6] the magnitude of the vertical velocity of the Hadley cell is estimated to be

$$W = \frac{H\Delta_H R}{\tau\Delta_v} = \frac{\Delta T R}{\tau\left(\frac{g}{C_p} - \Gamma\right)}, \tag{5}$$

where $\Delta_H = \Delta T/\langle T_E\rangle$, $\Delta_v = (g/C_p - \Gamma)H/\langle T_E\rangle$, $R = gH\Delta_H/\Omega^2 a^2$, $\langle T_E\rangle$ is the global average of the reference temperature, H is the tropopause height, and C_p is specific heat at constant pressure.

The Eulerian and TEM meridional stream functions for the standard experiments are shown in Fig. 1. The Hadley cell is clearly calculated in each hemisphere, but there are two maxima of the Ferrel cell. This is attributed to the use of the Newtonian cooling in the dry atmosphere. Nevertheless, the following argument will be valid for the qualitatively discussion. TEM circulation is

one cell structure in each hemisphere. In Fig. 1b), distribution of potential vorticity (PV) is shown for a reference. It can be seen that PV is almost constant along the stream line of the downward branch of TEM circulation.

To verify the dependencies on the control parameters, Γ, σ_T, τ C, ν, and α are changed. The relation between the intensities of the Hadley cell and the Ferrel cell (maximum values in the meridional plane) are shown in Fig. 2. It is confirmed that the intensity of the Ferrel cell is proportional to the intensity of the Hadley cell, and that the ratio is about 1/2 as predicted by Eq. (1). The dashed line in Fig. 2 is the dependency on Γ. and the dotted line is the dependency on τ. As expected from Eq. (5), as Γ is larger or τ is smaller, the Hadley cell is stronger, and, in accordance with this, the Ferrel cell is also stronger. Fig. 3 shows the relation between the intensities of the Hadley cell and TEM circulation. The intensities of TEM circulation is also proportional to that of the Hadley cell; it is 1.5 times as large as the Hadley intensity and is 3.0 times as large as the Ferrel intensity.

4. Conclusions

In general, the upward transport by the Hadley cell almost balances the downward transport by the Ferrel cell. The intensity of the Ferrel cell is determined by the supplied angular momentum. The angular momentum transport between the Hadley cell and the Ferrel cell is due to the eddy component and the value of the eddy transport can be estimated without detailed knowledge of the eddies. This, in turns, gives the intensity of TEM circulation. Since material transports are well described by TEM circulation, it can be said that the circulations in the lower-latitudes determine global mixing.

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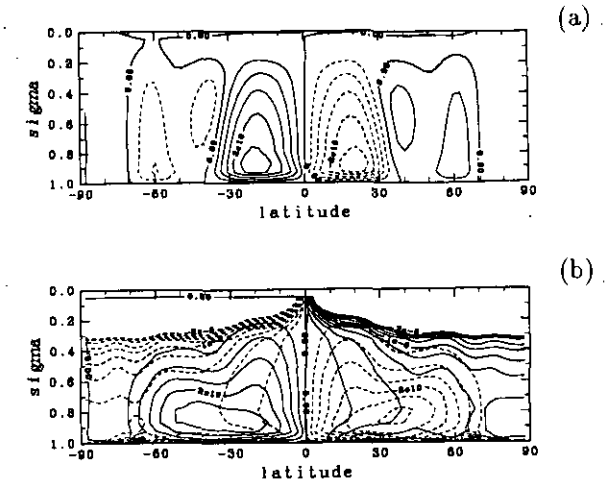

Figure 1. Distributions of (a) Eulerian and (b) TEM meridional stream functions for the standard experiment. The contour intervals are 5.0×10^9 kg/s. In (b), distribution of the potential vorticity is added (contour interval : 0.2PVU).

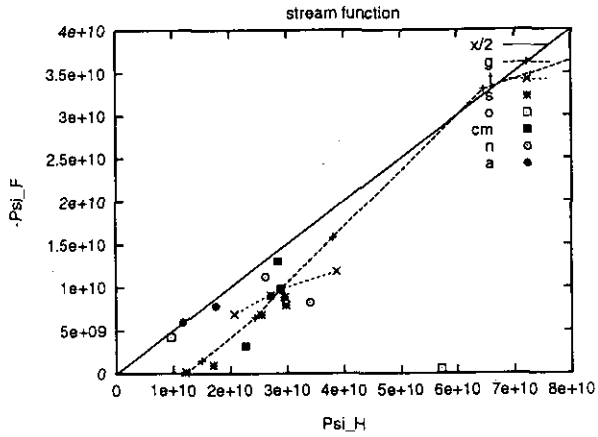

Figure 2. Relation beteen the intensities of the Hadley cell and the Ferrel cell.

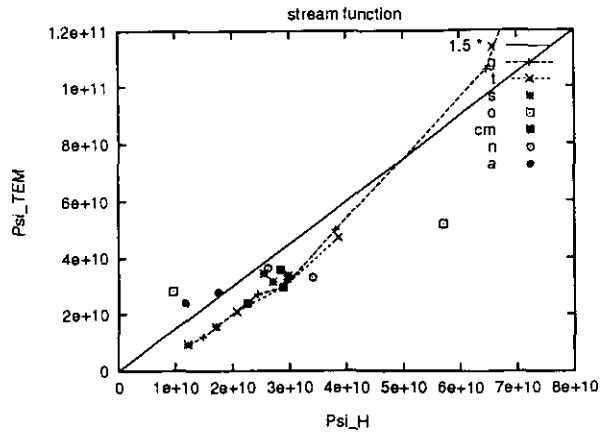

Figure 3. Relation beteen the intensities of the Hadley cell and TEM circualtion.