Hadley circulations in radiative-convective equilibrium in an axially symmetric atmosphere

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1.Introduction

The Hadley circulation is, in general, regarded as a horizontally convective cell which is driven by the north-south gradient of solar radiation heating. However, the differences of the solar heating in lower latitudes are not directly reflected to the atmospheric temperature, since most of the incident solar flux reaches the surface and the energy input into the atmosphere from the surface is in the form of latent heat. In the region of the Hadley circulations, there exists a balance among the supply of the latent heat from the surface, the heat transport by the circulation and the radiative cooling in the free atmosphere (e.g. Lorenz, 1967; Oort and Peixóto, 1983). In this sense, the Hadley circulation can be thought of as a vertically convective cell in the radiative-convective equilibrium.

The understandings of the dynamics of the Hadley circulation have been promoted by the studies of Schneider (1977) and Held and Hou(1980). They calculated the Hadley circulations using axially symmetric models, but do not explicitly consider the balance of radiation and moist convection.

In the present study, using an axisymmetric numerical model with simple but physically based schemes for the processes of radiation and moist convection, the behaviors of the Hadley circulation in radiative-convective equilibrium are investigated.

2.Model

The numerical model is based on the primitive equations for two-dimensional motions. The vertical coordinate is σ coordinate, where $\sigma = p/p_s$, p the pressure and p_s the surface pressure. The region considered is $-90° - 90°$ in latitudes, and $\sigma = 0 - 1$. The latitudinal grid has 100 points at intervals of $\Delta \sin\varphi = 0.02$, and the vertical grid has 50 points at intervals of $\Delta\sigma = 0.02$. The time integration is performed using the Euler backward scheme(Matsuno scheme), with a time step of $\Delta t = 2$ or 3 minutes. The troposphere is statistically equilibrated in about 100 days.

For the radiative process, a simple non-scattering grey radiative model is used. For the convection, the scheme with no parameterization of convection is used. The surface temperature is specified as

$$T_s(\varphi) = T_A - (T_B - T_A)\sin^2\varphi,$$

where $T_A = 300$ K, $T_B = 260$ K.

3.Results

The figure shows the mass streamfunctions of the equilibrium states for various values of the rotation rate, $\Omega = 0, 0.1, 1, 10 \times \Omega_0$, where Ω_0 is the terrestrial value. In the standard case ($\Omega = \Omega_0$; **C**), a systematic meridional circulation exists in the latitudes from the equator to about 20° in the upper layers and to about 10° in the lower layers. This meridional circulation corresponds to the "Hadley circulation", though the width is somewhat smaller than that of the real atmosphere. In the poleward regions of the Hadley circulation, there exist localized vertical convections. It should be noted that a steady indirect cell (the Ferrel cell) does not exist in the mid- and high-latitudes. The "troposphere", which consists of the Hadley circulation and the localized vertical convections, extends from the surface to the "tropopause", and the "stratosphere" extends from the tropopause to the top of the model atmosphere. The height of the tropopause is about 300 hPa at the equator, and becomes lower as the latitude increases. Because of the simplified radiative scheme, the tropopause height is much lower than that of the real atmosphere, but a choice of the radiative scheme will not have a significant effect on the subsequent arguments. The width of the Hadley circulation becomes broader as Ω decreases; the width is confined to about 2° for $\Omega = 10 \times \Omega_0$ while it is global for $\Omega = 0$.

For the standard case, Easterlies develop near the equator from the surface to the upper layers, and westerlies dominate in the poleward of the easterly region except for the bottom layers. In the poleward flow of the upper layers of the Hadley cell, the angular momentum is conserved and westerly becomes stronger in higher latitudes. A maximum of the westerlies is located at the poleward boundary of the Hadley cell. In the equatorward flow of the lower layers of the Hadley cell, the zonal wind is easterly in every latitude. In the stratosphere, the influence of the initial state remains as a weaker zonal wind in higher altitudes. The temperature is almost uniform in the latitudinal direction in the

Hadley cell. In the poleward regions of the cells, atmospheric temperatures depend on the value of the surface temperature at each latitude, and temperature profiles are determined so as to satisfy the local radiative-convective equilibrium. Between the latitudinally uniform region of temperature and the local radiative-convective equilibrium region, there exists a sharp boundary, which slopes from 10° in the lower layers to 20° at the tropopause.

The convections in mid- and high-latitudes have a systematic multi-cell structure. The scale of the cells is about 1,000 km, and they move equatorward at a speed of about 1m/sec. The surface zonal winds are easterly in the equatorial side of the upward motion of each cell, while they are westerly in the poleward side. No latitudinal belt of a steady surface westerly exists. Pairs of high and low pressures move equatorward as the convective cells move.

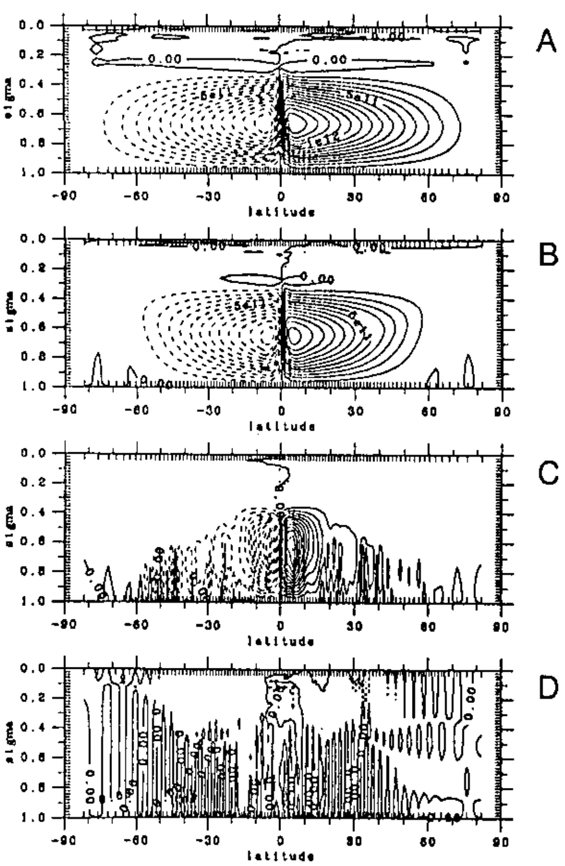

Fig. Meridional distributions of mass streamfunction for A: $\Omega = 0$, B: $\Omega = 0.1 \times \Omega_0$, C: $\Omega = \Omega_0$ (the standard case) and D: $\Omega = 10 \times \Omega_0$, where $\Omega_0 = 2\pi/(24 \cdot 60 \cdot 60)$ [rad/s] is the terrestrial rotation rate. Contour intervals are 1×10^{11} kg/s for A and B, and 2×10^{10} kg/s for C and D.

4.Summary

Using an idealistic axisymmetric model with the moist process, the Hadley circulation in radiative-convective equilibrium is investigated. In the region of the Hadley circulation, the vertical profiles of the temperature are close to the most adiabat of the region of the upward motion, and the temperature becomes uniform in the latitudinal direction. A sharp meridional gradient of temperature is concentrated in the poleward boundary of the Hadley cell. The upper level poleward flow conserves angular momentum, and the vertical shear of the zonal wind is in the cyclostrophic balance with the meridional gradient of the vertically averaged temperature. These properties can qualitatively be explained by the simple model of Held and Hou. The width of the Hadley cell can easily be predicted from the relationship between the profiles of the surface temperature and the vertically averaged temperature.

In the mid- and high-latitudes, there exists a systematic multi-cell structure: the horizontal scale of the cells is about 1,000 km and they move equatorward at a speed of $\sim$ 1 m/sec. There does not appear a steady indirect cell, a latitudinal belt of steady surface westerly nor a subtropical high pressure at the surface.

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