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Simulation of the Hadley circulation seasonal variation using a general atmosphere circulation model of medium complexity

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Abstract. In this paper, the Hadley circulation is simulated with the use of a model of medium complexity, its response to the atmosphere temperature changes is estimated. The stream function is used to estimate the tropical circulation changes. It is shown that with a temperature meridional gradient decrease, weakening of the Hadley circulation and its boundary movement to the poles occurs.

1. Introduction

Global climate changes, occurring at the present time, are characterized by warming in the upper troposphere of the tropical latitudes, as well as in the surface layer of high latitudes. In general, the averaged temperature on the Earth since the mid-nineteenth century has risen by $0.7\,^\circ$C. In the system of the general circulation of the atmosphere, the tropical circulation Hadley cell, plays the key role in forming the Earth's climate, transferring the energy and angular momentum in the direction of the pole. The location of large-scale arid subtropical zones and major subtropical deserts of the world to a large extent is formed by descending branches of HC. Thus, the understanding of how the structure and intensity of HC associated with the dynamics of arid subtropical zones may change in the conditions of global warming is of theoretical and practical interest. The detailed structure of the HC response to global changes is fairly complicated, because HC is influenced by many factors, including heat sources in the tropics, stability of the atmosphere, extratropical vortex dynamics and the atmosphere humidity. Data reanalysis of atmospheric points to an intensification of the Hadley circulation in the second half of the 20th century [1–4]. However, it is detected neither in the upper air sounding data, nor in most of the joint models of the general circulation of the atmosphere and the oceans, or in general circulation models of the atmosphere [1, 5]. Simple physical considerations (see, e.g., [6]) show that global warming will slow down the tropical circulation. Such a deceleration shows general circulation models [7], as is revealed in the analysis of observational data circulation Walker [8, 9]. However, it was unclear whether it is projected onto a zonally averaged component of the tropicals circulation. The analysis of satellite observations indicates to the fact that the HC border has moved in the direction of the pole over the past 27 years [10], the question is whether this part of the response to global warming, remains unresolved and requires an additional study. Researchers have identified several possible reasons for the HC movement to the poles: it is global warming, stratospheric cooling, the temperature of the oceans and a change in the baroclinic vortices phase rate [4,11,12]. The influence of the stratosphere circulation on the troposphere is confirmed by observation data, and, also, by the results of numerical experiments. It is shown that the cooling of the polar stratosphere and the strengthening of the polar vortex leads to strengthening the sub-tropical tropospheric wind. A maximal shift to the pole, associated with stratospheric cooling, falls on the spring period and is significantly more pronounced in the southern hemisphere. Despite this, in the models that take account of the destruction of ozone in the stratosphere, the shift of the Hadley cell border to the pole is less pronounced.

In [13], it is established that the expansion of the Hadley cell is determined by the latitude of the baroclinic instability. The global warming causes an increase of the static stability, and, respectively, the region of the baroclinicity moves to the North.

2. Numerical experiment

In order to assess the impact of climate changes on the tropical circulation, a spectral model of the general circulation of the atmosphere with "simple" physics was used. A detailed description of the model is given in [14].

In this model, the prognostic variables specified in (λ, μ, σ) coordinates, where λ is a longitude, $\mu = \sin\varphi$, φ is a latitude; $\sigma = \frac{p}{p_s}$ is a vertical coordinate.

In the first experiment, the influence of the stratosphere cooling on the troposphere circulation is estimated. The calculations with a spectral model are conducted with T42 spectral resolution and with a horizontal 128×64 grid. The calculations are conducted for the period of 5 years until attaining a stationary mode. As diagnostic fields, there are fields of velocity, pressure and temperature averaged for 50 records, which are taken with a step of one week. In order to understand how stratosphere polar vortex changes inflict on ground layer of the troposphere, zonally averaged fields of temperature, pressure and eastward wind taken on the bottom level ($\sigma = 0.97$) are considered.

The equation for temperature is the following:

$$\frac{\partial T'}{\partial t} = -\frac{1}{1-\mu^2}\frac{\partial (uT')}{\partial \lambda} - \frac{\partial (vT')}{\partial \mu} + D \cdot T' - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \kappa\frac{T\omega}{p} + \frac{T_R - T}{T_R} - k(-1)^n \nabla^{2n} T'.$$

Varying the function T_R, one can investigate the circulation sensitivity in terms of changes of its background state.

In [14], a numerical experiment simulating the influence of the stratosphere cooling on the troposphere circulation is described.

The radiative balance temperature T_R is written down as

$$T_R(\sigma, \varphi) = T_r(\sigma) + h(\sigma),$$

$$T_r(\sigma) = T_{tr} + (\Gamma_{\max} - \Gamma) H \ln \frac{\sigma}{\sigma_T},$$

$$h(\sigma, \varphi) = \begin{cases} \sin \frac{\pi}{2} \Big(\frac{\sigma - \sigma_T}{1 - \sigma_T} \Big) \Big(\Delta T_{NS} \frac{\mu}{2} - \Delta T_{EP} \Big(\mu^2 - \frac{1}{3} \Big) \Big), & \sigma > \sigma_T, \\ \omega(\varphi) \Gamma H \ln \frac{\sigma}{\sigma_T}, \quad \sigma \leq \sigma_T, \end{cases}$$

where $\Gamma_{\max}$ is a maximum temperature gradient is equal to 4, T_{tr} is the temperature at the tropopause, and σ_T is a value of σ at the tropopause. A degree of the radiative cooling is determined by the parameter Γ. The constants ΔT_{NS} and ΔT_{EP} are equal to 0 and 60 K, respectively.

In [4], it was proposed to use a distance between the zero contour lines of the stream function at an altitude of 0.5 bar for the diagnosis of motion of the boundaries of the Hadley cell

$$\Phi = \frac{2\pi a \cos \varphi}{\mathrm{g}} \int_0^{0.5} \overline{p_s v}\, d\sigma.$$

In the model that does not take into account the seasonal course and orographic heterogeneity, the response of the Hadley cell to the stratospheric cooling is weakly expressed (Figure 1). The impact of the stratosphere cooling on the troposphere is restricted to high latitudes of the Northern hemisphere (Figure 2).

The sensitivity of the Hadley cell to a change the temperature of the troposphere is investigated. The main features of climate change are the increase of temperature of the upper troposphere in the tropics, and, consequently, an increase of the static stability, and also the increase in the temperature gradient. Because it is interesting to observe seasonal changes of Hadley cell, seasonal course is added into the model.

In the control experiment, a radiative equilibrium temperature is written as

$$T_R = T_{tr} + (T_s - T_{tr}) \frac{\sigma - \sigma_T}{1 - \sigma_T},$$

where $T_{tr} = 210$,

$$T_s = \begin{cases} 243 + 60 \cos \varphi + 30 \sin \varphi \cdot \sin t^*, & \varphi > 0, \\ 228 + 75 \cos \varphi + 25 \sin \varphi \cdot \sin t^*, & \varphi \leq 0. \end{cases}$$

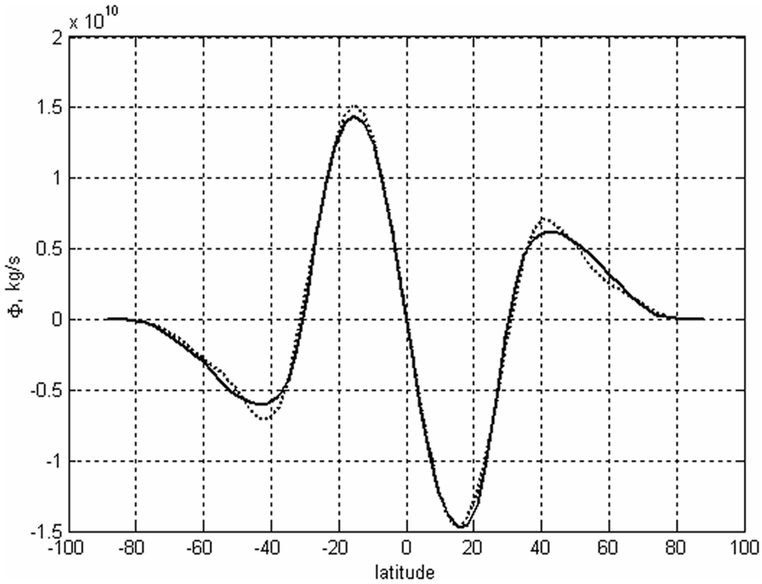

Figure 1. Stream function in the model without seasonal course and orography: the dashed line is for $\Gamma = 0$ and the solid one is for $\Gamma = 4$

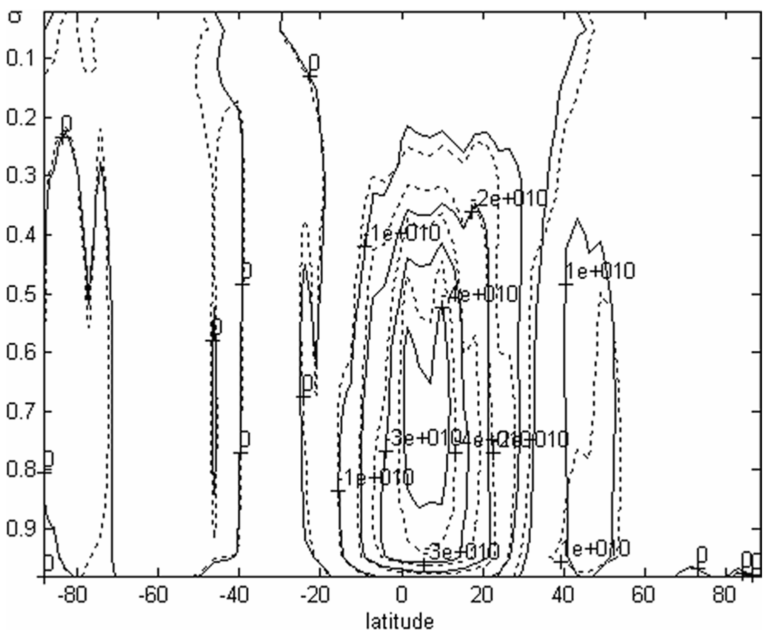

Figure 2. Stream function averaged for the winter period

In the experiment simulating the global warming, a maximum change of temperature at the surface was 5 K, a maximum temperature change in the upper troposphere is 6 K:

$$T_R = T_{tr} + (T'_s - T_{tr})\frac{\sigma - \sigma_T}{1 - \sigma_T} + \Delta T,$$

$$T'_s = \begin{cases} 248 + 55\cos\varphi + 30\sin\varphi \cdot \sin t^*, & \varphi > 0, \\ 233 + 70\cos\varphi + 25\sin\varphi \cdot \sin t^*, & \varphi \le 0, \end{cases}$$

$$\Delta T = \begin{cases} 6\dfrac{\sigma - \sigma_T}{\sigma_0 - \sigma_T}\cos\dfrac{\varphi}{2}, \quad |\varphi| \le \dfrac{\pi}{4}, \quad \sigma_T \le \sigma \le \sigma_0, \\ 6\dfrac{1 - \sigma}{1 - \sigma_0}\cos\dfrac{\varphi}{2}, \quad |\varphi| \le \dfrac{\pi}{4}, \quad \sigma \ge \sigma_0, \\ 0, \quad \text{otherwise}, \end{cases}$$

$\sigma_0 = 0.25$ is a height of a maximum warming. Dynamic fields for this experiment are calculated for the period of 11 years and with a step 10 days (Figure 3).

The intensity of the transport in the Hadley cell decreases when the climate change (warming in the lower troposphere of extra-tropical latitudes, and the upper troposphere of the tropics.

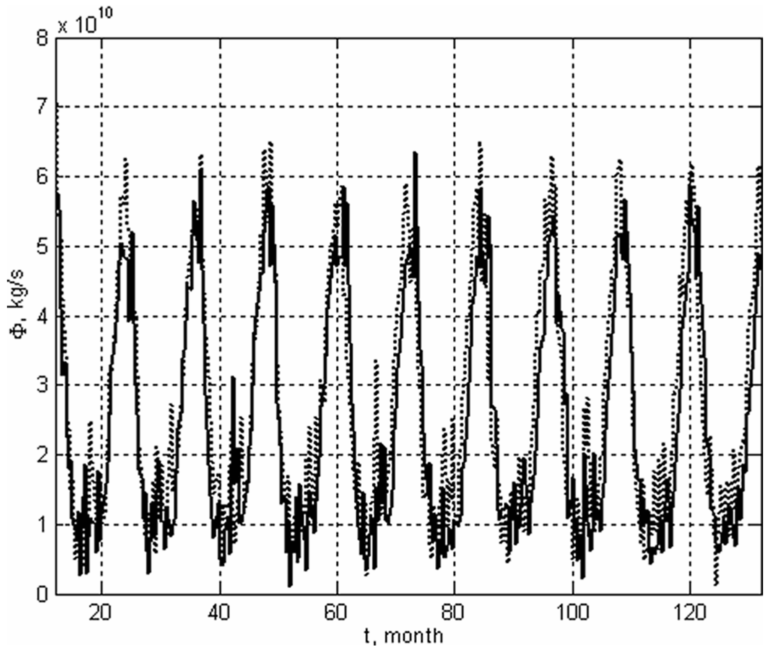

Figure 3. Maximum of a stream function in the Northern Hadley cell (kg/s). The dashed line is for the control experiment and the solid line is for warming

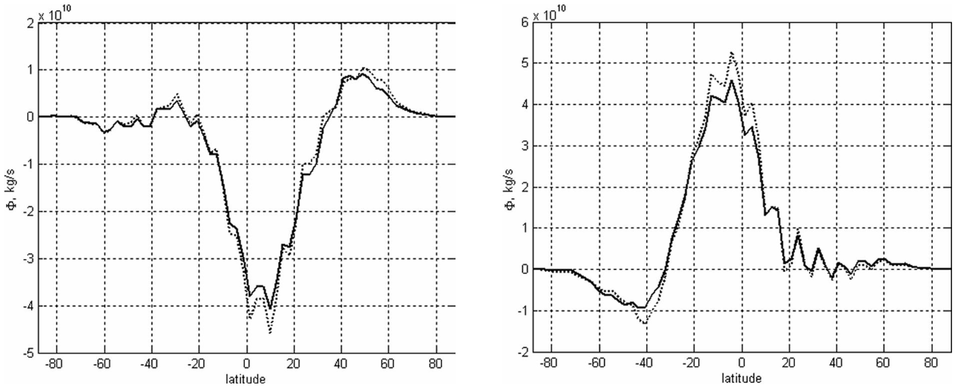

Figure 4. Graphs of the stream functions at the height $p = 0.5$ bar averaged for the period from December to February (left figure) and for the period from June to August (right figure). The dashed line is for the control experiment and the solid line is for warming

Figure 4 shows graphs of the stream functions at a height of 0.5 bar, depending on the latitude. In the chart for December–February one can see a shift of the boundaries of the Northern Hadley cell to the pole by, approximately, 3 degrees. Shifting boundaries of the South Hadley cell in the chart for June–August is less visible. It can be assumed that the cause of the motion of the Hadley cell boundaries to the poles, in addition to the global warming, are some of the factors which are not taken into consideration in the model in question, for example, the effect of the ocean currents. This shows the need for further studies of the causes of differences between the observations and the results of the simulation.

3. Conclusion

In the experiment of simulating only the stratosphere cooling, there are no response of the Hadley cell to climate changes. In the model used, the response of the troposphere to the stratosphere cooling is restricted in high latitudes.

Changes of the troposphere temperature have a strong influence on the Hagley circulation A decrease of the temperature gradient causes the weakening of the zonal Hadley cell. Natural variability of the Hadley cell boundary latitude in the conducted experiment is about 2 degrees. Thus, it can be said that a displacement of the latitude of the Hadley cell boundary is also significant. Studying the circulation sensitivity with the use of the considered model cannot be complete since it does not take into account many factors such as El-Nini phases and the related Walker ciculation variations, a hydrological cycle. It is obvious that the global warming is one of the most important factors responding to changes of the tropical circulation and to the climate zones movement. The proposed model of intermediate complexity does not reveal the Hadley circulation strengthening with an increase of static stability in the tropics. This is in agreement with the results of other researches using models of the dry atmosphere. But in a model with allowance for humidity it was obtained that with an increase of the static stability there occurs intensification of the Hadley cell. This enables us to conclude that changes in the moisture rotation under conditions of the global warning play the key role in the Hadley cell dynamics.

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