Earth's Rotation Causes Global Atmospheric Circulation.

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- The horizontal component of centripetal acceleration due to the Earth’s rotation causes the global circulation of the atmosphere.
- Polar and tropical tropopause separate circulation flows.
- The height of the tropopause raises with an increase in the Earth's rotation speed and a decrease in the temperature difference between the equator and the poles.
- Polar stratospheric clouds form when air rises near the poles around the tropical tropopause.

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Abstract

Understanding processes that determine the global circulation of the atmosphere is necessary for long-term weather forecasting and climate studies, which are critical for ensuring energy security. Processes in the atmosphere depend on many factors including the rotation of the Earth. The vertical component of the emerging centripetal acceleration is taken into account by introducing a geopotential height. The influence of the horizontal component is usually not taken into account, although these components are close in magnitude. Here, I describe a mechanism of circulation formation due to a non-hydrostatic pressure gradient resulting from centripetal acceleration, which is created by the Earth’s rotation. The effect is similar to the curvature of a water surface in a rotating vessel. This causes the unevenly heated air to move in a meridional direction. The circulation consists of three oppositely directed flows separated vertically by the polar and tropical tropopause.

Keywords: Global circulation of the atmosphere, the rotation of the Earth, polar and tropical tropopause, a non-hydrostatic pressure gradient

1. Introduction

The global circulation of the atmosphere determines the long-term variability of processes in the atmosphere. The temperature difference between the equator and the poles is called the cause of circulation (Prandtl 1952, Perevedentsev 2013). The pressure decreases faster with altitude in a cold air than in a warm air, so the pressure difference is formed between warm and cold regions, and it increases with altitude. Areas with an oppositely directed pressure gradient exist because they form the circulation in the atmosphere: air moves from an area with increased pressure to an area with reduced pressure. The air above the surface will shift to the equator and above a certain height with a zero gradient to the pole. Therefore, the surface pressure should increase from the equator to the poles. To make the position of the center of mass of the atmosphere constant, the total momentum flow in the atmosphere must be approximately constant in latitude. This condition can be used for a rough assessment of the nature of the change in surface pressure. The condition can be written as
\[ \int_0^\infty P_\varphi(h)dh = \text{const} \quad (1) \]

Where \( h \) is the height above ground level, \( P_\varphi(h) \) is the pressure at altitude \( h \) and latitude \( \varphi \). For an isothermal atmosphere, condition (1) leads to the following relation for the value of the surface pressure:

\[ P_\varphi = P_0 \frac{T_0}{T_\varphi} \quad (2) \]

Where \( P_0 \) is the surface pressure at the equator, \( P_\varphi \) is the surface pressure at latitude \( \varphi \), \( T_0 \) is the air temperature at the equator, \( T_\varphi \) is the air temperature at latitude \( \varphi \). Therefore, the surface pressure must increase monotonously from the equator to the pole. For a Hadley cell with a temperature difference of 10 - 15 degrees, the pressure difference is about 50 hPa. The observed pressure difference in the Hadley cell is noticeably smaller and does not explain the occurrence of circulation. The pressure difference between the equator and the poles should be about 300 hPa, which never happens. The viscous friction of the air flow against the surface will further increase the pressure drop. An additional pressure source is required for the formation of circulation.

2. The effect of the Earth's rotation.

The source of additional pressure may be the rotation of the Earth. The vertical component of the emerging centripetal acceleration does not create an additional horizontal pressure gradient. The horizontal component of centripetal acceleration due to the rotation of the Earth is capable of creating additional pressure. This effect is not taken into account in the theory of global atmospheric circulation (Prandtl 1952, Eckart 1960, Chamberlain 1981), since the horizontal component of centripetal acceleration (HCA) does not affect the hydrostatic pressure.

Fig.1. The occurrence of the horizontal component of centripetal acceleration along the meridian.
Nevertheless, an effect similar to the deformation of the liquid surface in a rotating vessel should be observed in the atmosphere. An estimate of the effect of earth rotation can be made for an isothermal atmosphere with a constant temperature $T$. The value of the HCA component directed along the Earth's surface is

$$a = \omega^2 R \cos \varphi \sin \varphi$$  \hspace{1cm} (4)

where $\omega$ is the angular rotational velocity and $R$ is the radius of the Earth, $\varphi$ latitude. Its value in the middle latitudes is about 0.02 m/s$^2$, which is about 500 times less than the acceleration of free fall. The relative pressure increment when the latitude of $\varphi$ changes to $d\varphi$ (dr = $R\,d\varphi$) taking into account the gas equation $P = \rho R_c T$ ($\rho$ - air density, $R_c$ - specific gas constant) is equal to

$$\frac{dP}{P} = -\frac{R^2 \omega^2 \cos \varphi \sin \varphi}{R_c T}$$  \hspace{1cm} (5)

Integration and substitution as a constant of the pressure logarithm at the equator $-\ln P_0$ at $\varphi=0$ gives

$$P(\varphi) = P_0 \exp \left( -\frac{R^2 \omega^2 \sin^2 \varphi}{2R_c T} \right)$$  \hspace{1cm} (6)

The pressure at the pole at an average atmospheric temperature of 290 K° is equal to 0.27 of the pressure at the equator. It should be noted that the pressure gradient due to HCA is about 7 Pa/km, which is comparable to the pressure gradients in cyclones and anticyclones. The dependence of pressure on the latitude and the altitude for an isothermal atmosphere can be recorded in the following form.

$$P(\varphi, h) = P_0 \exp \left( -\frac{gh}{R_c T} \right) \exp \left( -\frac{R^2 \omega^2 \sin^2 \varphi}{2R_c T} \right)$$  \hspace{1cm} (7)

The change in pressure due to HCA and hydrostatic pressure is the same, so the isothermal atmosphere will be in a state of equilibrium despite a significant surface pressure gradient.

If the temperature changes with latitude, then the vertical pressure gradient also depends on the latitude and the ratio (7) does not hold. It is important to determine the possibility of circulation in the atmosphere with the observed parameters.

3. Description of the circulation structure.

The rigorous justification of the circulation process is the subject of a separate study. Qualitative considerations are given below. It is based on empirical considerations that are valid in order of magnitude. The surface pressure can be considered constant. The temperature can be set in the following form

$$T(\varphi) = T_p + A \cos \varphi$$  \hspace{1cm} (8)

Where $T_p$ is the average temperature of the pole, equal to 240°K for the North Pole, and $A$ is the temperature difference between the equator and the pole, equal to 60°K. The average temperature for the South Pole is lower, but this is caused by its location at elevation, so the temperature of the North Pole is used for the estimate. The proposed ratio characterizes the temperature distribution with sufficient accuracy and reflects the main reason for the temperature change, namely, the change in radiation heating due to a change in the angle of incidence of sunlight.

The change of the sign of the pressure gradient in the static state occurs when the HCA and the hydrostatic pressure gradient are equal
\[ -\rho(\varphi,h)R^2\omega^2\cos\varphi\sin\varphi = \frac{dP(\varphi,h)}{d\varphi} \quad (9) \]

The expression for the height change of the pressure gradient sign for a static state is as follows:

\[ h = \frac{R^2\omega^2\cos\varphi T(\varphi)}{Ag} \quad (10) \]

The pressure gradient changes in the static state at an altitude of 105 km at the equator, and at the altitude of 9 km for a latitude of 85°. Thus, regions with an oppositely directed pressure gradient exist in the atmosphere at a constant surface pressure. In a dynamic state, viscous friction changes these values, but the height of the interface is also determined by the square of the angular velocity of the earth's rotation, temperature and the temperature difference between the equator and the poles.

The air between the Earth's surface and the surface with a zero pressure gradient shifts to the equator. Viscous friction occurs in the lower flow due to braking on the surface of the Earth. The resulting non-hydrostatic pressure gradient is determined by the velocity gradient and the viscosity coefficient. Non-hydrostatic pressure reduction due to viscosity is directed opposite to HCA and reduces its value. This is an equivalent to the reduction of \( \omega \) and, accordingly, \( h \) in the ratio (10).

The maximum effect will be in the surface layer of the atmosphere due to the large derivative of velocity in height. With increasing altitude, the meridional velocity increases, and a zonal component of the velocity appears due to the Coriolis force, which forms the boundary layer of the atmosphere with the Ekman layer.

The lower part of the flow from the pole to the equator heats up in the boundary layer from the surface as it shifts to the equator, and its upper part cools due to adiabatic expansion during ascent. Adiabatic expansion due to an increase in the perimeter of the Earth also contributes, but its contribution is difficult to estimate due to thermal contact with the surface. The vertical temperature gradient tends to be dry-adiabatic, which causes intense turbulent mixing. As a result, the flow of water vapor increases. Its condensation ensures the maintenance of a humid adiabatic temperature gradient.

The air above the surface with a zero pressure gradient shifts to the pole and creates a vacuum above this surface. Therefore, the air rises near the equator and cools. At some altitude, the air changes direction and head towards the pole. The height of the flow boundary corresponds to the polar tropopause and decreases towards the pole, since the nature of its behavior is described by the ratio (10).

The flow from the equator to the pole does not reach the surface, so the vertical temperature gradient is close to isothermal. The pressure gradient due to the viscous friction and HCA are summed up. The temperature of the flow when moving to the pole increases due to the lowering of the air and adiabatic compression causing by to a decrease in the perimeter of the Earth, which creates a temperature gradient opposite to the gradient on the surface of the Earth. At a certain distance from the equator, a decrease in the temperature gradient slows down the flow rate.

First of all, the change of the pressure gradient sign occurs at the top of the flow. The compression of the flow leads to an increase in the derivative of velocity and viscous friction. The viscosity coefficient in an isothermal atmosphere does not depend on the density of the air, so viscous friction primarily slows down less dense air. At some distance from the equator, the air at the top of the stream stops and conditions arise for the rise and movement of air in the opposite direction towards the equator. The excess air mass shifts upwards and then shift towards the equator. The shift towards the pole is hindered by a temperature gradient due to adiabatic air compression. As
a result, a second raised circulation cell with reverse air movement is formed above the near-surface one. The middle and lower part of the flow continues to shift to the poles.

The tropical tropopause separates the flows of this elevated circulation. The latitudinal boundary of this circulation is determined by the balance between many factors and varies greatly. The flow over the tropical tropopause rises and cools. At the same time, its upper part is heated by the ozone layer. The temperature contrast in the tropical tropopause arises as a result of the competition of many factors, so the maximum in the temperature profile will be little manifested in high latitudes.

Fig. 2. Structure of flows in the global circulation of the atmosphere. Circulation around the polar tropopause is highlighted in pink, around the tropical tropopause is highlighted in blue. The boundary layer of the atmosphere is highlighted in green. The temperature is shown by a red line. The red arrows show the movement of air with adiabatic heating, and the blue arrows show the movement with adiabatic cooling. The white arrow shows the movement of air with simultaneous heating from the Earth’s surface and adiabatic cooling. The polar tropopause is shown by a brown curve; the tropical tropopause is shown by a blue curve. A purple line shows the Junge layer. Polar stratospheric clouds are shown in yellow. The ozone layer is shown in orange. Arrows on a white background show the direction of the wind according to sounding data in Hawaii on October 11, 2021.

The structure of flows in the global circulation of the atmosphere is presented in Fig. 2. The constancy of the heights of both tropopauses is a consequence of the inertia of the zonal flows. The flow in the stratosphere is deflected by the Coriolis force, which forms a hollow rotating sphere. The local temperature change shifts the equilibrium, but the inertia of the zonal flow smoothes out these fluctuations. The direction of the viscous friction force changes sign in the tropopause. Therefore, strong wind shifts and jet streams should be observed here.

4. Compliance of the proposed circulation with experimental data.
If the above reasoning is correct, then the vertical profiles of atmospheric parameters will have certain characteristic features. The coincidence of the changes in wind direction and changes in temperature gradients corresponds to the heights of the flow separation. This coincidence is difficult to detect because of the low velocity of the circulation flows. The air is constantly in motion at a higher speed due to other processes, and calm conditions are required. However, sometimes mesoscale air movements weaken and make it possible to see a sharp change in wind direction. The data of upper air sounding are shown in Fig. 3 (http://weather.uwyo.edu/upperair/sounding.html).

Fig. 3. The results of upper air sounding, selected by the presence of a sharp change in wind direction near the tropopause. Arrows to the right of the diagrams show the wind direction. A line closer to the center of the diagram shows air temperature. On the left, the temperature of the dew point. Height is deferred along the vertical axis, the temperature of the C° is horizontal. The names of the stations and their latitude are indicated below the diagrams.

Upper air sounding data are shown in Fig. 3. Fig. 3a and 3b show the nature of the wind change in the middle latitudes in the Southern (3a) and Northern (3b) hemispheres. The change in wind direction is observed both at the height of the polar tropopause and at the tropical one, which corresponds to oppositely directed meridional flows. Consequently, below the polar tropopause is
the flow from the pole to the equator, above the polar tropopause there is the opposite one. Above the tropical tropopause, the stream is directed towards the equator. In the tropical zone, there may be no change in the temperature gradient at the height of the wind direction change (Fig. 3c). The circulation around the tropical tropopause sometimes extends to Antarctica (3d).

The poles of cold do not change their position when the inclination of the Earth changes due to rotation relative to the Sun. The position and distance between the updrafts of the Northern and Southern hemispheres are also determined by the HCA, which is confirmed by the relatively stable position of the Intertropical Convergence Zone. The proximity of descending air in the stratosphere and rising air in the troposphere causes the appearance of a tropospheric inversion layer (TIL) (Birner 2006) in the form of a sign-alternating temperature gradient. The air descends at the poles, so the position of the air lowering zones is determined by the pressure gradient due to HCA.

A humid air near the equator cools during ascent, which causes condensation of water vapor. When moving to the pole, the air descends and heats up, which leads to a sharp increase in the pressure of saturated water vapor. The actual water vapor pressure does not change, but the relative humidity decreases. As a result, a sharp change in the dew point temperature will be observed in the tropopause (Fig. 3). Turbulent mixing causes the transfer of aerosols from the surface to the atmosphere. In turn, aerosols cause the attenuation of the Sun’s radiation. A sharp change in the attenuation coefficient of visible light (Kochin 2021) is observed at the level of the polar tropopause, which indicates a sharp change in the concentration of aerosols. A change in the ozone-water vapor relationship is observed in the tropical tropopause (Pan L. 2013).

The specific evidence of different properties of flows near the tropical tropopause is the Junge layer. At an altitude of about 18 km, the air masses of the polar and tropical circulation are mixed, which causes the appearance at this altitude of a stratospheric aerosol layer. Air masses from the Junge layer rise by circulation around the tropical tropopause, which leads to the formation of polar stratospheric clouds (PSC).

In addition, the descending and diverging flow of dry air from the stratosphere must have some horizontal extent to allow for the passage of the total air flow. At a low flow height, the horizontal velocity has a large value. A possible consequence of the proposed mechanism could be the formation of an area with strong winds and lack of precipitation, known as the Dry Valleys in Antarctica.

The polar region is the most complex object. The HCA is rapidly reduced to zero there. However, the temperature gradient continues to form circulation on its own. In accordance with relation (2), circulation only due to the temperature gradient creates an area of increased surface pressure in an area with a lower temperature. This should lead to the appearance of areas of increased pressure directly near the poles, which is observed.

5. Discussion and Conclusions

Estimating the flow rate requires knowledge of the viscosity strength, which depends on the turbulent viscosity coefficient. There are no reliable experimental data on it. The velocity in the stratosphere is about 5 times greater than in the troposphere, because the mass flows are equal, and the air density in the stratosphere is less. The passage of air through the entire circulation cell may take several months (Prandtl 1952), but there is not enough data yet to clarify this value.
The temperature difference gives an approximately constant pressure gradient from the equator to the pole. The HCA increases to a latitude of about 30 degrees, which highlights the first zone in the atmosphere. Then it changes slightly between 30 and 60 degrees with a maximum of 45 degrees, which highlights the second zone. After 60 degrees, it decreases rapidly, which highlights the third zone. The Farrell cell is located between 30 and 60 degrees and coincides with the location of the second zone. However, spatial coincidence is not an explanation for the mechanism of formation. Apparently, there is some connection between the formation of the Farrell cell and the rotation of the Earth.

As mentioned above, the magnitude of the pressure gradient due to HCA is comparable to the pressure gradient in mesoscale processes (cyclones, anticyclones, etc.). Therefore, the results of the work are able to increase the reliability of the long-term weather forecast.

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