Hadley Circulation
(revised from I N James)

Jian Lu
4400 University Drive
MS 2B3
George Mason University
Fairfax, VA 20330
USA
E-mail: jianlu@cola.iges.org
Telephone: +1-301-902-1244

Gabriel A. Vecchi
Princeton University Forrestal Campus
201 Forrestal Road
Princeton, NJ 08540-6649
USA
E-mail: Gabriel.A.Vecchi@noaa.gov
Telephone: +1-609-453-6583

Abstract
The Hadley circulation, a prominent circulation feature characterized by rising air near the equator and sinking air in the subtropics, defines the position of dry subtropical areas and is a fundamental regulator of the earth’s energy and momentum budgets. The character of the Hadley circulation, and its related precipitation regimes, exhibits variation and change in response to both climate variability and radiative forcing changes. The strength and position of the Hadley circulation change from year to year paced by El Niño and La Niña events. Over the last few decades of the 20th century, the Hadley cell has expanded poleward in both hemispheres, with changes in atmospheric composition (including stratospheric ozone depletion and greenhouse gas increases) thought to have contributed to its expansion. This article introduces the basic phenomenology and driving mechanism of the Hadley circulation and discusses its variations under both natural and anthropogenic climate forcings.

Introduction
The ‘Hadley circulation’, named after George Hadley, an English Lawyer and amateur meteorologist, is perhaps the earliest attempt to account for the global-scale distribution of
winds in the Earth’s atmosphere in terms of basic physical processes. Halley in 1685 and Hadley in 1735 both proposed that the ‘Trade Winds’ that blow toward the Equator at low latitudes could be understood as the lower branch of an axially symmetric convection cell driven by the temperature difference between the Equator and poles of the Earth. Their ideas were ahead of their time, especially as there was then no prospect of determining winds at upper levels of the atmosphere and thus verifying their hypothesis. When routine upper-air observations became available in the mid-twentieth century, the ideas of Halley and Hadley were essentially confirmed. Today, the term ‘Hadley circulation’ refers to the zonally-averaged meridional overturning motions in the low-latitude troposphere.

Figure 1 provides a schematic view of the traditional global atmospheric circulation, dividing the Earth into a set of climate zones, with the Trade Wind regime confined to the tropics. The Trade Winds are simply the low-level part of the overturning ‘Hadley circulations’, with ascent near the intertropical convergent zone (ITCZ), descent in the subtropics and a poleward return flow at upper levels. The Hadley circulation plays a key role in transporting heat, moisture, momentum meridionally and is an indispensible component for understanding the global climate system and its variability. The descending branch of the Hadley Circulation sets the position of the dry subtropical regions (in which most of the world’s deserts are found) and is bounded on its poleward flank by the extra-tropical storm tracks, with mean surface westerly flow. The transition from easterly to westerly flow through the subtropics results in anticyclonic wind stress curl, which drives ocean surface convergence and results in large regions of suppressed ocean biological productivity. Thus, the poleward branches of the Hadley circulation set the location of the main land and ocean deserts, the former through reduced moisture supply and the latter through reduced nutrient supply. The more disturbed midlatitudes are characterized by generally westerly winds, with irregular growing and decaying eddies, the cyclonic and anticyclonic weather systems generated by baroclinic instabilities. When averaged around entire latitude circles, this turbulent midlatitude flow averages to a weak ‘Ferrel circulation’, in which warmer air at lower latitudes sinks and colder air at high latitude rises. There is some evidence of a very weak ‘polar cell’ at high latitudes.
The energy that drives the Hadley circulation comes from the conversion of heat energy to mechanical energy in the tropical atmosphere: the Hadley circulation is a prototypical example of a thermodynamic ‘heat engine’. Such heat engines are ultimately responsible for maintaining all motions in the atmosphere against the dissipative effects of friction. The operation of the atmospheric heat engine is shown in Figure 2, which is a classic thermodynamic diagram in which temperature is plotted against specific entropy. The thermodynamic state of an air parcel – that is, its temperature, pressure, density and so on – are represented by a point on the thermodynamic diagram, and any change of its thermodynamic state by a curve on the diagram. The area under the process curve is proportional to the heat energy entering an air parcel. The diagram also shows two different lines of constant atmospheric pressure, one near the Earth’s surface and one in the tropical upper troposphere. Near the surface, air flows toward the Equator, along the segment marked AB, gaining heat from the surface (in a manner not so differently from the boundary layer inflow into the eye of a hurricane). Near the Equator, it rises almost adiabatically (that is, with little heat entering or leaving the air) along the segment BC. It then moves poleward along segment CD, largely maintaining its temperature and angular momentum. The overturning cell is closed by a subtropical descent, as denoted by segment DA, during which the air parcel loses entropy by emitting infrared radiation to space. During this cyclic process, more heat is added to the air along AB and BC than is removed along CD and DA, with the net gain of heat being proportional to the area enclosed by the loop ABCD in the diagram. The excess heat is converted to mechanical energy associated with the circulation of the tropical air.

The condition for such an energy conversion to take place is that heat should on average be added at higher pressure than it is removed. Equivalently, one can say that air must rise on average when it is warmer, and descend when it is cooler. A circulation with these properties is called a ‘thermally direct circulation’. A thermally indirect circulation, in contrast, must be driven by a source of mechanical energy; a refrigerator cycle is an example of such a thermally indirect circulation. In the schematic diagram of Figure 2, the
Hadley circulation is thermally direct, and therefore generates mechanical energy. In contrast, the Ferrel circulation of midlatitudes is thermally indirect and consumes mechanical energy.

The observed annual mean meridional circulation is shown in Figure 3. The contours are parallel to the northward and upward winds averaged around latitude circles and in time. The contour values have been scaled to have units of kg s$^{-1}$. They may be thought of as denoting the mass flux across a line from the edge of the plot to that point. The most striking feature is the strong rising motion near the Equator, and sinking motion at latitudes of about 25°N and 25°S, defining two overturning cells, the ‘Hadley cells’, one in each hemisphere. However, the actual winds associated with these circulations are not particularly strong: they barely exceed 5 ms$^{-1}$. The diagram also reveals that there is a close relationship between the westerly component of the wind, shown by the grey shading, and the meridional flow. The westerly component is much stronger, with values up to 40 m s$^{-1}$.

These maximum winds, the so-called ‘subtropical jet’, are found in the upper troposphere, just where the circulations associated with the Hadley cells meet those associated with the Ferrel cells. There is also a close relationship between the zonal winds and the temperature fields: they are linked, to a very good approximation by the thermal wind relationship, which can be written as eqn [1], where $u$ and $T$ denote the zonal wind and temperature averaged around latitude circles, respectively; $p$ is pressure, which decreases with height, and is often used as the vertical coordinate for the governing equations for the atmosphere; and $R = 287\ J\ kg^{-1}\ K^{-1}$ is the specific gas constant for dry air.

$$\frac{\partial u}{\partial p} = \frac{R}{pf} \frac{\partial T}{\partial y}$$

That is, a strong vertical wind shear is associated with a strong poleward temperature gradient. In the deep tropics where the Coriolis parameter $f$ is small, this relationship indicates that the temperature gradients must be small, whatever the wind field. But in the subtropics and midlatitudes, the increasing westerly wind with height is associated with the fall of temperature toward the poles.
The Held-Hou Model

An elegant model due to Held and Hou (1980) gives considerable insight into the Hadley circulation and the factors that determine its extent. Figure 4 illustrates a two-layer representation of the model. The lower layer is affected by friction at the ground, and flow within it is supposed to be generally small. Friction is effectively zero in the upper layer and so at this level rings of air conserve their angular momentum as they move poleward.

Assuming that such rings start at the Equator with zero zonal wind relative to the solid earth, the wind at higher latitudes in the upper layer is given by eqn [2], where $\Omega$ is the rotation rate of the Earth, $a$ is the radius of the Earth, and $y$ is the distance from the equator, proportional to the latitude.

$$ u_M = \frac{\Omega}{a} y^2 \quad [2] $$

Eqn [2] implies that the zonal wind of an air parcel that conserves angular momentum increases rapidly with latitude as it moves poleward. Using the principle of thermal wind balance in the form of eqn [3], the formula for $u_M$ can be used to predict the variation of temperature with latitude, $T_M(y)$.

$$ \frac{\partial u_M}{\partial z} = \frac{ga}{2\Omega y} \frac{\partial T_M}{\partial y} \quad [3] $$

Substituting [2] into [3] and solving for $T_M$, one can see that the upper layer air temperature in conformity with the constraint of angular momentum conservation is proportional to the fourth power of the latitude. That is, $T_M$ is flat near the equator and drops rapidly at subtropics. This is to be compared with the hypothetical ‘radiative equilibrium’ temperature distribution $T_E(y)$ of an atmosphere that is not permitted to circulate. Where the actual temperature is less than radiative equilibrium there is net heating, and vice versa. In a steady state, this heating and cooling should exactly balance in the Hadley circulation and this requirement fixes the meridional extent and strength of the Hadley circulation.

Figure 5 illustrates a graphical solution of the Held–Hou model. The actual temperature
varies very little with latitude in the tropics but drops rapidly in the subtropics and mid-latitudes. The radiative equilibrium temperature has a maximum at the Equator. The temperature on the equator is set by requiring that there be no net heating of air parcels as they circulate, that is, that the area shaded in red must be equal to the areas shaded in blue. The poleward limit of the Hadley circulation is at the latitude where these curves cross for the second time. A formula for the distance of the poleward edge of the Hadley cell from the equator results from this solution:

\[ Y_H = a\phi_H = \sqrt{\frac{5gH\Delta T}{3\Omega^2 T_0}}, \]  

where \( \Delta T \) is equator-to-pole temperature difference, \( T_0 \) the global mean temperature, and \( H \) the vertical extent of the Hadley cell. This formula suggests a value for \( Y_H \) of about 2500 km, in good agreement with observations considering the simplicity of the model.

The model can be elaborated. For example, the vertical motions, proportional to the heating in the regions of ascent and descent, can be estimated. The model predicts a vertical circulation that is rather weaker than that observed. The effect of latent heat release in cumulonimbus clouds, which leads to intensified but narrower ascent, and broad regions of descent, can be represented. But the basic physics, which predicts that the Hadley circulations are confined to 2500 km or so of the equator, remains relevant.

**Seasonal Effects**

The annual mean circulation shown in Figure 3 is in fact the average of two quite different circulation regimes that persist around the solstices. Figure 6 shows the circulation for the mean Northern Hemisphere winter and summer seasons. In both cases, there is a single strong thermally direct winter Hadley cell with rising motion in the summer hemisphere and descent in the winter hemisphere, while the strength of the summer cell is very much suppressed. Weaker, thermally indirect Ferrel cells are seen at middle latitudes in both hemispheres. Looking at the mean circulation for shorter periods reveals that the transition
between a circulation like that of Figure 6A and one like that of Figure 6B is quite abrupt. At most times, there is just a single tropical Hadley cell whose circulation links the two hemispheres: at some point in the spring and autumn its direction of circulation switches abruptly as the insolation maximum crosses the Equator.

The Held–Hou model can be adapted to the situation where the heating is not symmetric about the Equator. Assume that the maximum radiative equilibrium temperature is no longer at the Equator, but at some latitude $\phi_0$. As well as the latitude of the northern and southern edges of the Hadley cells, the latitude $\phi_C$ of the streamline that divides circulation into the summer and winter hemispheres, and which is not the same as $\phi_0$, must be determined. The algebra is a little more complicated, but the steps in the argument are just the same as for symmetric Hadley cell described in the previous section.

Figure 7 shows the results. For even small $\phi_0$, the summer cell shrinks drastically and the winter cell intensifies. Almost all the circulation is associated with ascent in the summer hemisphere and with descent in the winter. The strength of the circulation is indicated by the area between the temperature curve and the radiation equilibrium curve. For $\phi_0$ of only 5°, the winter cell has intensified by a factor of about 10 compared to the symmetric case, while the summer cell has weakened by a similar factor. The winter cell is therefore some 100 times as intense as the summer cell. Such a highly nonlinear response to the latitude of the heating maximum means that the annual mean meridional circulation is much more intense than the circulation derived from the annual mean heating. This is a particularly pointed example of the problem of ‘nonlinear averaging’, which is ubiquitous in the study of climate. This result also reconciles the weak circulations of the Held–Hou model with the stronger observed circulation: we should interpret the annual mean circulation as the average of the two solstitial circulations, not as the response to the annual mean thermal forcing.
The Eddy Mediating Effect on the Hadley Circulation

The structure of the Hadley cell is not entirely determined by the tropical heating, fluctuations in the flow (often termed ‘eddies’) also play a significant role in shaping the intensity and structure of the Hadley circulation. The momentum and heat transport by eddies acts to amplify the subtropical portion of the Hadley cell. Evidence suggests that eddies, rather than the energetic closure, have more direct relevance to the terminus of the Hadley cell. An alternative view of how the width of the Hadley cell is determined is that angular-momentum conservation of the upper tropospheric zonal wind continues pole-wards until the resulting vertical shears become baroclinically unstable (Palmén and Newton 1969; Held 2000). If one uses the two-layer model’s criterion for instability, the terminus of the Hadley cell occurs at the latitude where

$$ \frac{\partial H}{\partial y} = \frac{\beta H_0}{f}, $$

where $H$ is the thickness of the upper layer, indicating the tropospheric mean temperature, $H_0$ is the mean thickness. From thermal wind balance,

$$ g^* \frac{\partial H}{\partial y} = f(u_1 - u_2), $$

with the low layer wind $u_2 \approx 0$, then, in the upper layer the criterion can be expressed as

$$ u_1 \approx \beta \frac{g^* H_0}{f^2}, $$

where $g^* \equiv \frac{\rho_2 - \rho_1}{\rho_1} g$ is reduced gravity. Invoking the small angle approximation for algebraic simplicity, the terminus of the Hadley cell can be obtained by equating the baroclinically unstable wind with the angular-momentum conserving wind, that is, $u_1 = u_M$. This leads to alternative formula for the width of the Hadley cell:

$$ Y_{Bc} = \alpha \phi_{Bc} = \left( \frac{g H_0}{\Omega^2 \Delta_v} \right)^{1/2}, $$

where $\Delta_v$ is the fractional change in potential temperature in the vertical, representing the bulk static stability of the air column. Substituting into [8] the parameters typically observed
for the Earth’s climate would give a Hadley cell width of 2500-3000 km, also in good agreement with the observations.

One could combine the two scaling theories for the Hadley cell width by saying that the Hadley cell stops at the smaller of $Y_{BC}$ and $Y_H$. If $Y_H < Y_{BC}$, the flow would become unstable before reaching the axisymmetric limit. If $Y_{BC} < Y_H$, on the other hand, the Hadley cell would terminate before becoming baroclinically unstable. Unfortunately, $Y_H \approx Y_{BC}$ based on the observed parameters, rendering it difficult to discern which mechanism is actually operating in the atmosphere. Evidence from analyzing observational data and data from climate models suggests that the instability-based scaling theory is more relevant to the terminus of the Hadley cell in reality. In addition, scaling relation [8] seems to capture the sensitivity of the Hadley cell width to a range of climate change perturbations. The scaling relation [8] can be easily generalized for inter-hemispherically asymmetric situations. See the schematic in Figure 8 for details.

Near the subtropical edge of the Hadley cell, the vertical motion is mainly maintained by the eddy momentum drag via the so-called ‘eddy-pump’ effect, and the edge of the Hadley cell tends to align with the transition point between divergence and convergence of the eddy momentum fluxes. Therefore, a third view interprets the Hadley cell terminus as the latitude poleward of which vertical eddy activity fluxes are sufficiently deep to reach the upper troposphere and begin to propagate meridionally, leading to the eddy momentum flux convergence/divergence. However, this midlatitude-centric view has yet to be verified against the observations and more realistic AGCM simulations.

**Hadley Circulation under Climate Change**

Hadley circulation plays a key role in transporting moisture, momentum and energy in the tropical atmosphere. It also serves as an important conduit for inter-hemispheric exchange and tropical-extratropical interaction between the thermally direct circulation and the eddy-
driven circulation. Both the intensity and structure of the Hadley circulation can vary due to natural climate variability as well as external climate forcings. For example, El Niño, a climate event that occurs every a few years with an anomalous sea surface temperature warming in the central and eastern equatorial Pacific, can drive an intensification and contraction of the Hadley cell. In accordance to the Hadley circulation response, the midlatitude westerly jet and storm track also shift equatorward. And vice versa for a La Niña. Climate change forcing agents, including greenhouse gases, ozone, aerosols, all can impact on the Hadley circulation.

Increasing the concentration of greenhouse gases can lead to the expansion of the Hadley cell. Since the majority of earth’s driest and arid regions are located in the areas underneath the descending branches of the Hadley circulation around 30° latitude, the expansion of the Hadley circulation can lead to significant changes in precipitation in the latitudes near the edge of the cells. As the areas around the latitudes of the Hadley cell edge become drier, those inhabiting those regions will see less rainfall than traditionally expected, which could cause major problems with water supplies and livability. The mechanisms for the global warming induced Hadley cell expansion can be complicated. Studies suggested that the amount of the expansion seems to match the scaling relation [8] and attributed the expansion to the increase of the subtropical atmospheric stratification (i.e., \( \Delta_v \)) under greenhouse warming of the climate.

In fact, we have just witnessed an expansion of the Hadley cell in both hemispheres during the last few decades of the 20th century. The Southern Hemispheric expansion has been largely blamed on the depleting trend of the stratospheric ozone over Antarctica since the late 1970s. The stratospheric ‘ozone hole’ in the austral spring to summer not only shifts the jet stream and the storm tracks but also causes the austral summer Hadley cell to expand. These circulation changes result in decrease of precipitation around 45°S and increase of precipitation around 60°S associated with the poleward-shifted storm track, as well as moistening in the subtropics over the southwestern Indian Ocean, eastern Australia, and southern flank of the Southern Pacific Convergence Zone (SPCZ). The causes for the
Northern Hemisphere Hadley cell expansion are more complicated. Aerosols (especially black carbon), tropospheric ozone (as a greenhouse gas), and multidecadal trend of SST might all have contributed to the expansion in the Northern Hemisphere.

Since industrial revolution, the industrial activities has been polluting the Northern Hemisphere more than the Southern Hemisphere, thus imposing an inter-hemispherically asymmetric forcing to the Earth’s climate due to the dimming effect of the pollutants. In balancing this radiative perturbation, the ‘thermal equator’, where the meridional energy transport of the atmosphere crosses zero, should shift towards the relatively warmed hemisphere since it now does not need as much energy input through transport as it otherwise would. As a consequence, the ITCZ as well as the Hadley cells shifted southward. This response, it is believed, has contributed to the devastating drought and famine throughout the Sahel nations in the 1960s-80s. In fact, any inter-hemispheric asymmetric forcing for the Earth climate system, including the seasonality in the solar irradiance, orbital forcing, melting of polar ice, oceanic heat flux associated with the Atlantic meridional overturning circulation, etc., can all potentially shift the Hadley cell and ITCZ.

A Lagrangian View

The diagrams of the meridional circulation shown so far have all been based on so-called ‘Eulerian averages’. That is, the winds have been averaged at fixed points in space to produce the time-mean, zonal-mean circulation. At all points in space, the winds and temperatures fluctuate to some degree as weather systems pass across the observing site. An alternative is to follow individual elements of fluid as they move around in the atmosphere, and average their properties to define a mean circulation. Such a mean is called the ‘Lagrangian mean’, and in many ways is a much preferable way to describe the circulation. For example, the laws of physics applied to the atmosphere all refer to the properties of discrete, identifiable lumps of fluid. However, the Lagrangian mean is very difficult to calculate in practice, not least because individual elements of fluid rapidly become distorted and eventually thoroughly mixed with neighboring elements.
An approximation to the Lagrangian meridional mean circulation can easily be calculated, and is shown in Figure 9. In constructing this diagram, the wind data were averaged not on surfaces of constant pressure (as in Figures 3 and 6) but on surfaces of constant ‘potential temperature’. The potential temperature of an air parcel generally remains more or less constant for periods of less than a few days. It follows that surfaces of constant potential temperature move up and down in response to the movement of the air. Averaging on potential temperature surfaces is equivalent, to the degree that potential temperature is indeed conserved, to taking the Lagrangian average.

Figure 9 differs dramatically from the corresponding Eulerian mean circulation shown in Figure 6. The tropical Hadley cell is still present, but the mid-latitude, thermally indirect Ferrel is largely eradicated. Instead, a thermally direct circulation extends all the way from the tropics to the pole in the winter hemisphere. The original picture of the global circulation suggested by Halley and Hadley is largely vindicated if one views the circulation in Lagrangian terms.

The thermally indirect Ferrel cell actually transports heat against the temperature gradient, from high latitudes to low latitudes. At the same time, eddies more than compensate by transporting heat down the temperature gradient, from low latitudes to high. In fact, the partitioning of the flow into mean and eddy parts is arbitrary. The Lagrangian circulation, dominated by thermally direct circulations at nearly all latitudes, is a more natural and less arbitrary description. However, the Eulerian depiction of the Hadley circulation remains to be relevant and significant in terms of its dynamical impacts on climate.

**Cross References**


**Relevant Websites**
**Figure 1** A schematic view of the mean circulation of the troposphere. The arrows on the globe show the winds near the Earth’s surface. The cells at the side show the zonal mean circulation cells at various latitudes.
Figure 2 A schematic thermodynamic diagram for the Hadley circulation.
Figure 3 The annual mean meridional streamfunction. Contour interval is $2 \times 10^{10}$ Kg s$^{-1}$. Shading shows zonal winds greater than 20 m s$^{-1}$. Based on an analysis of 44 years of ERA40 reanalysis.
Figure 4 The configuration of the Held-Hou model.
Figure 5 Solution of Held-Hou model.
Figure 6 The mean meridional circulation for (A) the December-January-February season and (B) the June-July-August season. Other details are as for Figure 3.
Figure 7 As Figure 5, but for a situation in which the heating maximum is located away from the Equator. $\phi_0$ is the latitude of maximum radiative equilibrium temperature, $\phi_C$ is the latitude dividing the winter and summer Hadley cells, $\phi_W$ and $\phi_S$ designate the limits of the winter and summer Hadley cells, respectively.
Figure 8 Schematic for a scaling relation that distinguishes between winter and summer Hadley cells. The thin solid line indicates the angular momentum conserving zonal wind profile \( u_M \), obtained under the assumption of \( u = 0 \) at the ITCZ \( \phi_i \). The red lines represent the baroclinic instability criterion for two-layer model. Their intersections with the zonal wind profiles (thick lines) determine the edges of the Hadley cell. The zonal wind in summer cell deviates more from \( u_M \) compared to the zonal wind in winter cell due to the greater damping effect from the mid-latitude eddies.
**Figure 9** The mean meridional circulation for December-January-February (DJF), March-April-May season (MAM), June-July-August (JJA), and September-October-November (SON), but with the data zonally averaged on surfaces of constant potential temperature rather than on surfaces of constant pressure. Gray lines show median surface potential temperature. Contour interval is $2.5 \times 10^{10}$ kg s$^{-1}$. Computed from ERA40 reanalysis. Adopted from Walker and Schneider (2006).
Further Reading


Hadley E (1686) A historical account of the trade winds, and monsoons, observable in the seas between and near the tropics, with an attempt to assign the physical cause of the said winds. Philosophical Transations of the Royal Society of London 16: 153-168.


