

Hadley Cell (HC) Circulation response to Climate Change and Global Warming Projections

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1. Introduction and Motivation

Hadley circulation was first proposed by Sir George Hadley and Sir Edmund Halley in 1735. When they proposed an explanation for the observed wind patterns in the tropics. Hadley circulation is a large scale circulation over the tropics. It consists of the zonally averaged meridional circulation: north to south, in the north hemisphere; south to north in the south hemisphere; converging at the equator, and rising, and then a return flow at upper levels, back to the extra tropics, with subsidence. (See section 2.1). It has seasonal and interannual variability.

Recent studies have shown the relationship between the HC circulation and other large-scale systems at higher latitudes (subtropical jets, subtropical highs, etc.) and, also interactions with other interannual oscillations as El Niño Southern Oscillation (ENSO) and the Monsoon circulation. One of the characteristics that makes the HC important to study is the Inter-Tropical Convergence Zone (ITCZ), that arises from the convergence of the wind from the north and the south at the equator; hence its intensity is directly related with the precipitation over the tropics.

Changes in Hadley circulation such as strengthening, weakening and movement are important for human activities because, as it has been said before, this circulation is related with the precipitation over the tropics, and other large-scale circulations that affect human activities with changes in surface winds, precipitation, droughts, etc.

The oceans play an important role as part of the Hadley circulation. It is related with the difference in sea surface temperatures (SSTs) over the ocean due to the seasonality of solar radiation. Tanaka et al. (2003) showed that the Hadley circulation exist even in a hypothetical aqua planet (no continents and no land-sea contrast), as long as this heat contrast imposed by the sun does not change (more radiation at the tropics, less radiations at higher latitudes). They concluded land-sea temperature contrast is more related with monsoon circulations rather than Hadley circulation. Thus this circulation would be affected by the changes in SSTs over the ocean due to climate change.

In the Intergovernmental Panel on Climate Change (IPCC) report of 2007, on Chapter 3: Observations: Surface and Atmospheric Climate Change, in section 3.7: Changes in the Tropics and Subtropics, and in the Monsoons; they discuss the change, that according to some studies, the Hadley circulation would have as a result of climate change:

“ Tropical SSTs determine where the upward branch of the Hadley Circulation is located over the oceans, and the dominant variations in the energy transport by the Hadley cell. ... Examination of the Hadley Circulation in several data sets (Mitas and Clement 2005), suggest some strengthening, although discrepancies among reanalysis data sets and known deficiencies raise questions about the robustness of this strengthening, especially prior to satellite era (1979). ” (Trenberth et al. 2007)

Changes in the tropical circulation patterns generates a response mechanism in the atmosphere and ocean localized not just in the tropics. Mitas and Clement, 2005 explained that studies in the radiation budget in the atmosphere suggest an increase of the long-wave radiation emitted by the earth and a reduction of the short wave radiation reflected from the sun. They argued that it had been suggested that these changes are related with the intensification of the tropical atmospheric circulation, specially the HC. An increase in the intensity of the HC is traduced in an increase of upper motion at the tropics (ITCZ), this will increase the cloudiness (cloud-fraction) and the humidity in the ITCZ, with a decrease of the cloud-fraction at the subtropics.

Thus, is important to study the possible changes of this tropical feature under a climate change environment, and the consequences that they would have by the increase of anthropogenic greenhouse gases. The present paper describes the principal changes that Hadley circulation will have due to climate change, according to the result of different Atmospheric-Ocean Global Climate Models (AOGCM).

2. Trends of the Hadley Circulation

2.1 HC overview

Hadley circulation is the circulation resulting for the pressure gradients forces arising from the differential radiative heating between the equator and the poles, this produce a tendency for the warm tropical air to rise and for the cold polar air to sink resulting in a vertical meridional plane, as a direct circulation.

It is driven by meridional circulation with ascending motion in the equator, which leads to the Inter-Tropical Convergence Zone (ITCZ); and a descending motion over the subtropical high pressure belt. Dynamically, the available potential energy in the form of temperature gradients across the latitude would get converted into zonal kinetic energy.

The Halley-Hadley Model, shown in figure 1a, has a meridional extension of all the latitudes, posterior studies after this first theory, proposed Ferrell cells and the Hadley circulation cell is shown in figure 1b.

The HC has a well defined seasonal cycle, during the summer of the north hemisphere the cells move northward, and during the winter they move southward back to the equator.

The interaction between the HC and the ocean is complex, and more studies are need on the subject. Although that is not the topic of this

paper, in order to illustrate the complex nature of these process and to emphasize the important of the ocean in the HC circulation, figure 2 is shown. It is an schematic cross section of the atmosphere and the ocean interactions.

The intensity of the HC is defined in terms of a mass stream function ψ , this function is obtained by the mass conservation equation expressed using pressure as a vertical coordinate, the value of the mass stream function at a given latitude and pressure level is equal to the rate at which the mass is transported meridionally or vertically, $\left([\psi] = \frac{kg}{s}\right)$. (Cook 2004):

$$\frac{1}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{1}{a \cos \phi} \frac{\partial (v \cos \phi)}{\partial \phi} + \frac{\partial w}{\partial p} = 0$$

Where: u : zonal component of the wind, v : meridional component of the wind, w : vertical component of the wind, p : pressure, ϕ : latitude, λ : longitude, and a : radius of the earth.

The stream function is defined as: $\psi(\phi, p) = \frac{2\pi a \cos \phi}{g} \int_0^p [v(\phi, p)] dp$

$$\text{Then: } [\bar{v}] = \frac{g}{2\pi a \cos \phi} \frac{\partial \psi}{\partial p} \text{ and } [\bar{w}] = -\frac{g}{2\pi a^2 \cos \phi} \frac{\partial \psi}{\partial \phi}$$

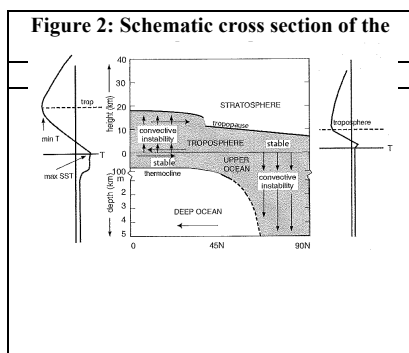
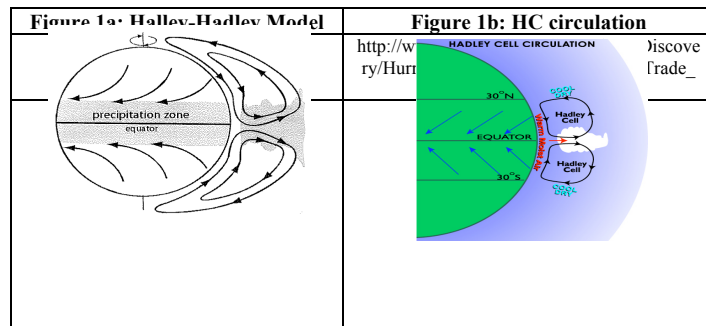
Where: $[\bar{v}]$: meridional component of the wind averaged zonally, $[\bar{w}]$: vertical component of the wind averaged zonally.

In several studies the HC strength is quantify using: $[\bar{v}]_{200} - [\bar{v}]_{850}$. (Oort and Yienger 1996).

2.2 Change of the HC in the past years

Several studies have been made about the change in the HC due to Climate Change in the past years. Owada Akiyama (private communication), indicated that the Hadley circulation has increased its intensity in the last two decades, and the recent trend is argued as a connection with the global warming.

Observational studies have shown an increase on the SST, specially in the tropics and the south of Indian Ocean. The spatial distribution of radiative fluxes in the tropics is mainly determined by the



Hadley Cell and Walker cell overturning circulations, in the meridional and zonal plane respectively. (Chen et al 2002).

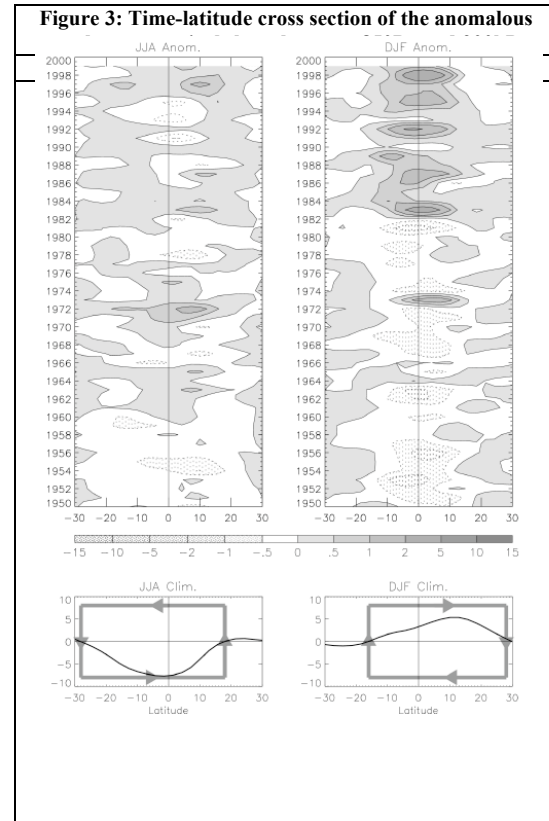
Quan et al. (2004), made a study of the change of the Hadley cell in the past 50 years, they use different data sets: National Center for Environmental Modeling/ National Center for Atmospheric Research (NCEP/NCAR) reanalysis, from January 1948 to 2000 they used monthly values of wind at 17 pressure levels and at a horizontal resolution of 2.5×2.5 degrees. 50 year ensemble of the Atmospheric Climate Model develop by the European Center for Medium Range Forecast (ECMWF), at Max-Planck Institute Hamburg (ECHAM-3). The simulations were forced by monthly global SSTs, the horizontal resolution of the model is 2.8×2.8 degrees. They used also the Global Precipitation Climatology Project (GPCP) data set with the satellite rain gauge precipitation data set.

Quan et al. 2004 obtained the differences between the zonal mean of the meridional component of the wind between 850hPa and 200hPa, in order to quantify the strengthening of the Hadley Circulation. They calculated a climatology for these values from NCEP-NCAR. The 50-year series for these values are compared and they observed important behavior of the HC circulation in the past 50 years. Both, NCEP/NCAR reanalysis and ECHAM3 show that during the wintertime in the north hemisphere: (December, January and February (DJF)) the intensity of the HC has increase since 1950. Figure 3 shows the difference between these values since 1950 until 2000, according with the 50 years ensembles made with ECHAM-3 in comparison with the climatological differences. They proposed that this strength on the HC was relate with the increase of SSTs in the past 50 years (See figure 3) and with the change of the statistical properties of ENSO during this period.

Mitas and Clement 2005, made an study similar to Quan et al. 2004, and addressed the question of the HC effectively was increasing its strength and if the SSTs are the principal cause for this tendency. In this case they used 5 data sets: NCEP/NCAR reanalysis (Kalnay et al. 1996), NCEP-DOE (Kamitsu et al., 2002), and ECMWF – 40 year reanalysis project (ERA40), the Geophysical Fluid Dynamics Laboratory of Atmospheric Circulation Tape Library of reanalyzed observations from rawinsonde, 15-member ensemble mean of the Community Atmospheric Model (CAM v2.0.1) initialized by the Atmospheric Model Intercomparison Project (AMIP) SSTs. In their study, Mitas and Clement conclude that the strength of the Hadley Cell is present in all the data sets used, but in each set the amount of increase, in terms of the stream function over time is different, for the case of NCEP/NCAR, the increase is of about $7.5 \times 10^8 \frac{Kg/s}{year}$ while using ERA40, is $21.3 \times 10^8 \frac{Kg/s}{year}$, which is consistent with the radiation measurements with satellites, and with other previous studies.

Tanaka et al. 2004 in his study of the trend and variability of the Walker, Monsoon, and Hadley circulation found out that the Hadley cell intensifies around $37 \times 10^5 \frac{m^2}{s}$ (velocity potential units, assuming that the vector-field of velocities can be written as a scalar function potential.)

One of the major critiques made by the scientists mentioned in the previous paragraphs is the differences found between datasets, i.e NCEP-DOE (NCEP2 reanalysis) with respect to NCEP/NCAR reanalysis; Mitas and Clement 2005 found that there was a reduction up to 50% of the albedo over the tropical oceans. They proposed that this difference affects the vertical structure of the HC circulation in both cases. They also claimed the necessity of more observations in the tropics, specially over the ocean in order to monitor the behavior of the HC.



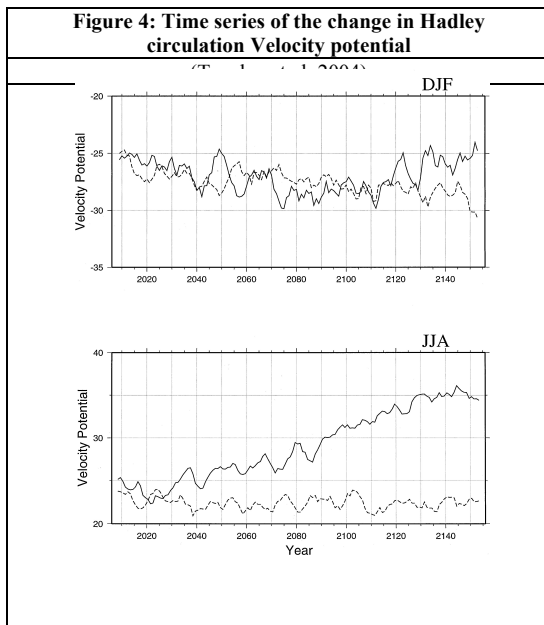
2.3 Trend of HC under Global Warming Projections

Projections of the response of the HC to global warming is studied through atmospheric-ocean coupled global climate models ran future times; the “global warming factor” is included in to the model as the increase of Carbon Dioxide in the atmosphere.

Tanaka et al. 2004 used the coupled Atmosphere-Ocean General Circulation Model from the Meteorological Research Institute of Japan (MRI-CGCM1), with a gradual increase in CO₂ at a rate of 1% /year during 150years.

He found that from 2000 to 2150, there is a significant change of the HC as a response to global warming, during JJA. The increase is of 40% ($25 - 35 \frac{m^2}{s}$) (See figure 4); they proposed it is due to the change in SSTs over the ocean. According to their model outputs for the period, they found out that the change in SSTs is greater over the Atlantic than the pacific, and that this differences of temperatures result on an zonally enhancement of upward motion that causes intensification on the HC.

Figure 4 shows the time series of velocity potential for the MRI-CGCM1 from 2000 - 2150. The dashed line is the time series for the control run (without the increase in CO₂), and the solid-line is the time series for the runs with the increase in CO₂. From this figure is clear the increase in magnitude of the HC during JJA; but during DJF the trend is not obvious (Tanaka et al. 2004).



3. Discussion and Conclusions

Some studies show evidence of the strengthening of the HC in the past years. Specially during the boreal winter (DJF). The majority of the authors agree that this change is due to the increase of the SSTs (See section 2.2).

Under global warming projections, Tanaka et al. 2004, based on model outputs, proposed the intensification of the HC up to 40% during JJA. There are not many studies in this subject; hence more investigation is needed in order to make a solid conclusion about the future behavior of the HC under global warming projections (see section 2.3).

The response HC under different climate conditions is complex and depending on the external forcing imposed. With the increase of the greenhouse gases in some models, the resulting SST would be a configuration similar to a El Niño year, and this produce an intensification in the HC circulation. But

this result is not persistent in all the Atmospheric-Ocean models.

It is difficult to consider if the changes that already happened in the past to this circulation are due to climate change or a natural fluctuation of the circulation, the same as the results obtained by numerical models for climate change scenarios (Clement 2006).

Is important to keep in mind that both, the projections under global warming and the study of the strengthening of the HC correspond to runs of AGCM or the reanalysis of these runs with the assimilation of observations; thus is necessary to consider the uncertainties associated with the models runs in both cases. There should be an evaluation, for the reanalysis runs.

In order to make the proper evaluation of the results of these reanalysis and model runs, is necessary to have a well defined observation channel in the tropics, in the atmosphere and the ocean. These days the observations not just in the tropics, around the world also, are very separated in space and time, and they are mostly over land, hence new challenges in the observational and instrumental fields arrive every day for meteorologist and oceanographers i.e how to address the lack of sampling in the observation array.

Although the investigation in this subject is complicated, it is important to keep working on this matter and try to address the issues observed, specially because changes of any kind in the HC would be reflected in the earth as a whole: rain fall in the tropics (ITCZ), radiative balance, monsoon systems, ocean circulation, meridional fluxes of heat, and humidity.

4. References

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