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# Widening and weakening of the Hadley circulation under global warming

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ABSTRACT

The Hadley circulation is one of the most important atmospheric circulations. Widening of the Hadley circulation has drawn extensive studies in the past decade. The key concern is that widening of the Hadley circulation would cause poleward shift of the subtropical dry zone. Various metrics have been applied to measure the widening of the tropics. What are responsible for the observed widening trends of the Hadley circulation? How anthropogenic and natural forcings caused the widening? How the widening results in regional climatic effects? These are the major questions in studing the widening of the Hadley circulation. While both observations and simulations all show widening of the Hadley circulation in the past few decades, there are no general agreements of changes in the strength of the Hadley circulation. Although some reanalysis datasets show strengthening of the Hadley circulation, it was shown that the strengthening trend could be artificial, and simulations show weakening of the Hadley circulation for global greenhouse warming. In the present paper, we shall briefly review the major progresses of studies in trends in width and strength of the Hadley circulation. We address answers to these questions, clarify inconsistent results, and propose ideas for future studies.



## 1. Introduction

The Hadley circulation is a zonal-mean meridional atmospheric circulation. It transports energy and angular momentum from the tropics to the subtropics. As one of the most important atmospheric circulations, it must demonstrate changes in width and/or strength in responding to global warming, and the changes should in turn have important influences on regional climate changes in both the tropics and subtropics. Thus, trends in the Hadley circulation have been an intensive research area in the past decade.

Both observations and simulations have demonstrated that the Hadley circulation has gone on poleward expansion in both hemispheres [1,2]. Moreover, simulations showed that the widening trend continues as greenhouse gases are kept increasing [3,4]. The reason why climatologists are so interested in widening of the Hadley circulation is because it implies a poleward shift of the subtropical dry zone, which corresponds to the descending branch of the Hadley circulation. Indeed, observations have shown that widening of the Hadley circulation has generated regional climatic effects, especially in the Southern Hemisphere (SH) [5,6]. That is, the southern Australia and Amazon have declining trends in precipitation. Because of its important climatic effects, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) has considered widening of the Hadley circulation and its regional climate impacts as an important issue [7]. Five of the fourteen chapters of IPCC-AR5 had assessments on widening of the Hadley circulation and its impacts on regional climates.

While multiple independent analyses have all identified widening of the Hadley circulation during the past few decades [8], there is no a general agreement whether the strength of the Hadley circulation has been significantly intensified or weakened [9]. The purpose of the present paper is to briefly review major progresses and controversies on trends in width and strength of the Hadley circulation, and to provide perspectives for future studies.

## 2. Different definitions

There are two terminologies that are alternatively used to characterize widening of the tropical atmospheric circulations. One is "widening (poleward expansion) of the Hadley circulation", and the other one is "widening of the tropical belt". Although the two terminologies are the same in the general sense, the latter has a broader meaning than the former because the tropical belt

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includes not only the Hadley cells but also other physical and chemical metrics such as, precipitation, outgoing longwave radiation (OLR), stratospheric ozone concentration, and so on. Here, we shall just focus on widening of the Hadley circulation.

For the Hadley circulation, the location of the subtropical zero line of the mean meridional mass streamfunction is used to define its width. The averaged total widening of the Hadley circulation (the sum of widening of both northern and southern Hadley cells), derived from multiple reanalysis datasets, is about 1° in latitude per decade [2]. For the tropical belt, various metrics are used to define its width, such as the location of the subtropical jet stream, the maximum meridional gradient of subtropical tropopause height, the maximum OLR, the maximum sea-level pressure, the zero difference of subtropical precipitation and evaporation (P-E), and the width of the tropical zone with relatively low total column ozone. Because these various metrics emphasize different properties of the tropical atmosphere, they yield a wide range of widening trends in the tropical belt [8,10]. Nonetheless, these trends from different metrics all demonstrated widening of the tropical belt.

## 3. Seasonality of widening trends

Unlike other metrics, widening of the Hadley circulation demonstrates large seasonal variations [1]. Fig. 1 shows the poleward shifts of poleward edges of Hadley cells in both hemispheres, derived from seven reanalyses. In each hemisphere, widening trends in summer and autumn seasons are large and statistically significant in general, while trends in winter and spring seasons are much weaker and insignificant. The seasonality of widening trends implies that the associated radiative forcings either have seasonality or co-operate with the Hadley circulation only in particular seasons in causing widening trends. It was suggested that the widening of the SH Hadley cell is mainly due to the Antarctic Ozone Hole that has the largest radiative cooling effect in the lower stratosphere in austral summer [11]. Increasing black carbon and tropospheric ozone in the Northern-Hemisphere (NH) extratropics are considered the major forcing in causing widening of the Hadley circulation in boreal summer [12], which have the largest warming effect in the NH extratropics. Simulations showed that increasing

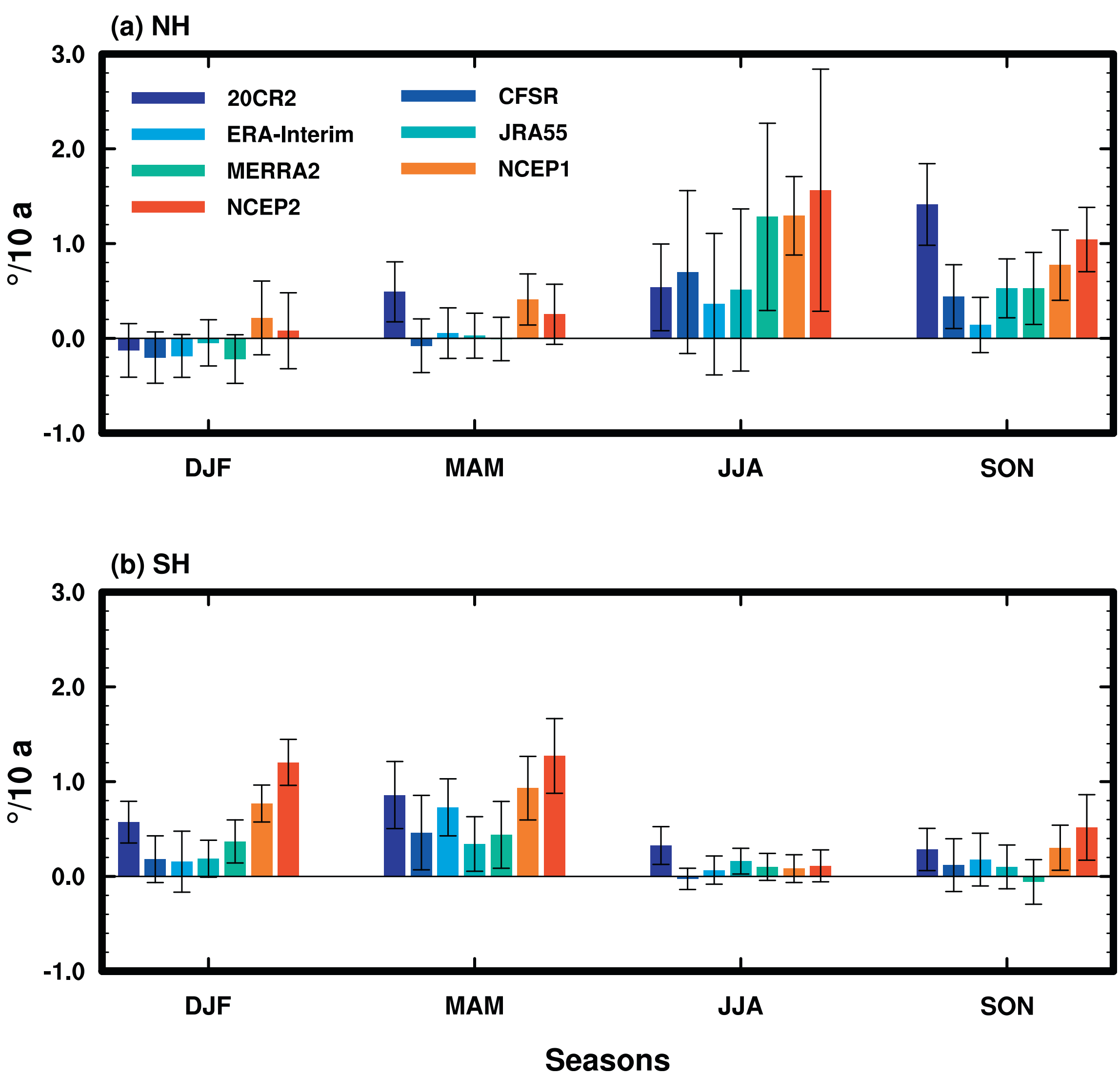


**Fig. 1.** Widening of the Hadley circulation for four seasons: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON), derived from seven reanalysis datasets. (a) NH, and (b) SH. The trends are calculated over 1979–2016. The unit of the vertical axis is degree per decade. Error bars are ±1.7 standard deviations. Updated from Hu and Fu (2007).

greenhouse gases (GHGs) force the largest widening of the NH cell in boreal autumn [4]. Because the radiative forcing of GHGs has no seasonality, the GHG forcing must be throughout some mechanisms in causing widening of the NH cell in boreal autumn. However, the associated mechanism is unknown.

## 4. Radiative forcing, and observations versus simulations

As mentioned above, increasing GHGs, stratospheric ozone depletion, and increasing tropospheric ozone, black carbon, and anthropogenic aerosols are considered the external forcings. The effect of each individual forcing and their total effect on the widening trends are assessed with simulation results from the Coupled Model Intercomparison Program Phase 5 (CMIP5) [4]. It is found that increasing GHGs cause widening of the Hadley circulation in both hemispheres, with the largest widening trend in the NH cell in boreal autumn. Stratospheric ozone depletion causes widening of the SH cell in austral spring and summer, and widening of the NH cell in boreal spring. Anthropogenic aerosols have no significant effects on the width of the Hadley circulation. Simulations also showed that increasing tropospheric ozone causes significant widening of the NH cell in boreal spring, summer and autumn, and that increasing black carbon results in NH cell widening in all seasons [12].

Changes in sea surface temperatures (SST) are also considered an important factor in causing widening of the Hadley circulation [13,14]. In fact, simulations with prescribed observed SST generated larger widening trends than that in CMIP5 simulations [4]. A recent simulation work, also with prescribed observed SST, argued that a large part of the observed widening trend in the NH cell might be caused by natural SST variations, especially by the cold phase of Pacific Decadal Oscillation (PDO), and that the part related to global greenhouse warming is secondary [14]. It suggests different effects between radiative forcing and natural SST variations on atmospheric circulations [15].

It is important to note that simulated widening trends are much weaker than that in observations [16,2]. The total widening trend derived from CMIP5 historical simulations is only about 0.17° per decade, which is about 6 times weaker than that from reanalysis datasets. Given that the observed widening trends are largely associated with the PDO that was in its cold phase in the past few decades [17], the much weaker trends in CMIP5 are likely due to poor performances of models in simulating SST temporal-spatial variations. Thus, it requires further studies to understand why there is so large discrepancy of widening trends between observations and simulations and whether PDO plays so large role in causing widening of the Hadley circulation.

## 5. Forcing mechanisms

Widening of the Hadley circulation is a response of atmospheric dynamics to atmospheric thermal structure changes caused by radiative forcing. It was noticed from satellite observations that the subtropical zone of the troposphere has stronger warming than other latitudes in both hemispheres [18]. It indicates that the relatively sharp meridional temperature gradients in the subtropics moves toward the extratropics. The thermal structure changes lead to poleward shifts of the subtropical jet streams. In consequence, baroclinic eddies retreat poleward, so that the Hadley circulation is able to maintain angular momentum conservation and extends further poleward [19,20].

Diagnostics based on CMIP3 simulations suggested that global greenhouse warming causes weakening of baroclinic eddies in the subtropics, and that the weakening of baroclinic eddies is because of increasing static stability [3]. This argument is based on the global warming configuration in climate simulations, that is, the middle and upper troposphere is warmed more than the lower troposphere in subtropics. However, reanalysis datasets demonstrate that the reduction of vertical wind shears in the subtropics is more important in causing weakening of baroclinicity [21]. According to the thermal-wind relation, reduction of vertical wind shears corresponds to weakening of meridional temperature gradients, which is indicative of enhanced warming in the subtropical zone.

Another mechanism is associated with changes in thermal structure contrast around the tropopause. Increasing GHGs cause tropospheric warming and stratospheric cooling. Moreover, stratospheric ozone depletion, especially the Antarctic Ozone Hole, also causes cooling in the stratosphere. These together sharpen meridional temperature contrasts between the lower stratosphere and upper troposphere and thus accelerated westerly winds in the extratropics. This causes an increase in the phase speed of upper-tropospheric baroclinic eddies. The faster moving eddies are unable to penetrate as far equatorward, resulting in a poleward shift in eddy momentum flux convergence and an associated poleward shift of the position of the eddy-driven subtropical jet and widening of the Hadley circulation [22]. Because ozone depletion is much more severe in the Antarctic stratosphere than in the Arctic stratosphere, this mechanism particularly works well for widening of the SH cell. Simulations showed that the SH jet streams shift equatorward as the Ozone Hole recovers in the 21st century [23].

## 6. Weakening or strengthening

There has been no theory on the relationship between Hadley cells' width and strength so far. Based on interannual variations in observations, the Hadley circulation is usually stronger and narrower for El Niño events, and it is weaker and wider for La Nina events [24]. Fig. 2 compares the composited Hadley circulation in December-January-February (DJF) between El Niño and La Nina events. It is obvious that the Hadley circulation is stronger and narrower in El Niño years than in La Nina years. It appears that in El Niño years the anomalously warm tongue along the Pacific equator would generate stronger and more concentrated ascent motion in the deep tropics. Thus, the descent branch of the Hadley circulation is also concentrated toward the equator. An earlier work, based on an idealized model, also showed that the Hadley circulation becomes stronger and narrower as the equatorial surface heating is more concentrated to the equator [25]. Overall, these works suggest an anti-correlation between the width and strength of the Hadley circulation. According to these works, the spatial pattern of tropical SST, especially its meridional distribution, is at least one of the key factors in determining the width and strength of the Hadley circulation on interannual time scales [26]. It is not clear whether such a relationship is valid over decadal time scales. If it is the case, the Hadley circulation would be wider and weaker in the cold PDO phase than in the warm phase [14,17].

Reanalysis datasets demonstrate inconsistent results of changes in the strength of the Hadley circulation as the climate is warming [9]. Among reanalysis datasets, ERA-40 yields the largest positive trend in the strength of the Hadley circulation. However, it was shown that the positive trend is artificial because ERA-40 generates unrealistically large positive trends in tropical precipitation [13]. The large precipitation trend suggests that there is increasing upward motion in the tropics in ERA-40, which causes strengthening of the Hadley circulation. This artificial trend in tropical precipitation no longer exists in its new version of reanalysis. It was also shown that the strengthening of the Hadley circulation in some reanalysis datasets is because of an artificial cooling in the tropical

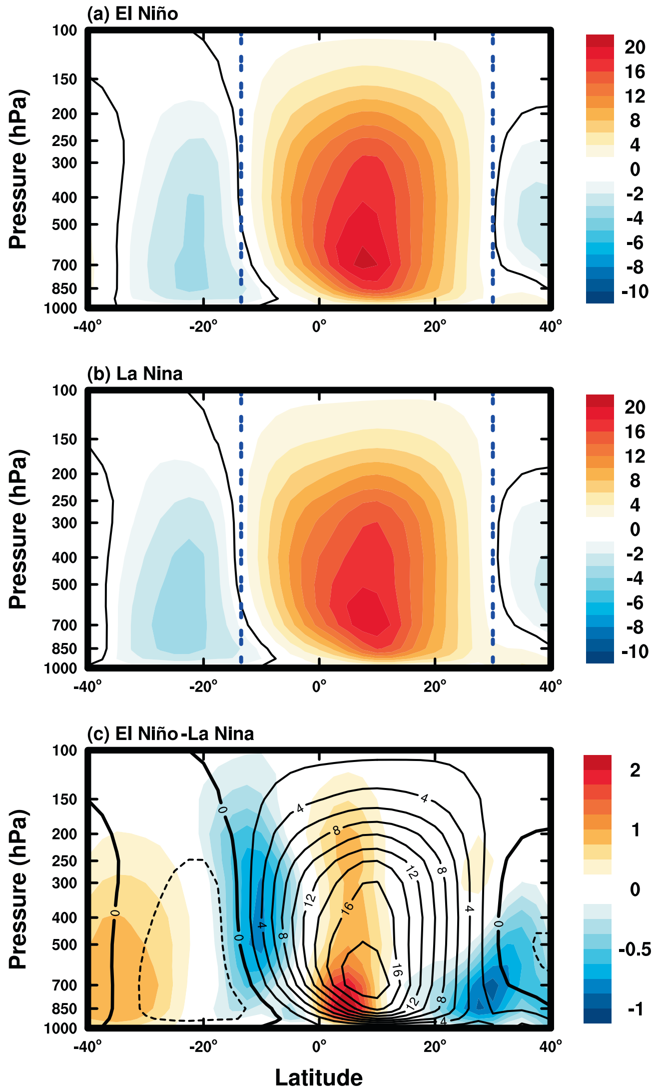


**Fig. 2.** Comparison of the Hadley circulation in DJF between compositions of El Niño and La Nina events. El Niño compositions are the events of 1982/1983, 1987/1988, 1992/1993, 1997/1998, 2002/2003. La Nina compositions are the events of 1985/1986, 1988/1989, 1999/2000, 2000/2001, 2007/2008, 2010/2011. The mass streamfunctions are calculated from NCEP2 reanalysis. Solid lines denote clockwise mass streamfunctions, and dashed-lines denote anti-clockwise mass streamfunctions. In all the plots, the unit is $1.0 \times 10^9$ kg s$^{-1}$.

middle troposphere due to systematic errors in these reanalyses [9]. The artificial cooling leads to enhanced upward motions of the tropical atmosphere, resulting in strengthening of the Hadley circulation.

In CMIP5 historical and projection simulations, widening of the Hadley circulation is all accompanied with a weakening of the strength [3]. For simulations with individual forcings, results are different. Increasing GHGs generate widening and weakening of the Hadley circulation, which is similar to the case of all-forcing historical and projection simulations. However, ozone only forcing produces widening and strengthening of the SH cell, without significant changes of the NH cell. Anthropogenic aerosol forcing has no significant impacts on both width and strength of the Hadley circulation.

It is worth pointing out that radiative forcings impact not only on the atmosphere but also on SSTs in simulations with coupled atmosphere-ocean models such as CMIP5. In fact, changes of atmospheric thermal structures are a combined result of direct radiative effects and SST changes. However, there have been no studies on how these individual forcings lead to changes in SST patterns, and how the simulated SST patterns influence on the strength and width of the Hadley circulation, while most studies have just focused on the effect of atmospheric thermal structure changes.

## 7. The Hadley circulation versus monsoon circulations

Monsoon circulations are regional meridional circulations. The direction of summer monsoon circulations is opposite to that of the Hadley circulation. It remains great challenges of what implications widening and weakening of the Hadley circulation have for regional monsoon circulations, and how changes of regional monsoon circulations contributed to the trends in the zonal-mean Hadley circulation. One difficulty is how to define regional meridional circulations. There were studies on trends in regional-mean meridional mass streamfunctions, using decomposed divergence winds. However, it is not clear how realistically such transformed regional mass streamfunctions can well represent regional meridional circulations. There were also studies to discuss the interannual relationship of the strength of Hadley circulation with monsoon circulations [27]. However, to our knowledge, there have been no works on the relationship of the width between the zonal-mean Hadley circulation and regional monsoon circulations.

## 8. Summary

Multiple independent datasets show widening of the Hadley circulation in the past few decades, while there are no consistent results of trends in the strength of the Hadley circulation. CMIP5 historical simulations also show widening of the Hadley circulation. However, the simulated widening trends are much weaker than that in reanalyses. Simulations demonstrate that increasing GHGs and stratospheric ozone depletion are the major radiative forcing in causing widening of the Hadley circulation. Natural SST variations may also a contributor to the observed widening trends. Radiative forcing alters atmospheric thermal structures, resulting in poleward retreat and weakening of baroclinic eddies in the extratropics. It consequently leads to poleward expansion of the Hadley circulation. Reanalysis datasets yield inconsistent trends in the strength of the Hadley circulation, while CMIP5 historical and projection simulations all demonstrate weakening of the Hadley circulation under global warming.

## Conflict of interest

The authors declare that they have no conflict of interest.

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