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Poleward Expansion of the Hadley Circulation in CMIP5 Simulations

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ABSTRACT

Observational analyses have demonstrated that the Hadley circulation has expanded poleward in recent decades. Important issues are what caused the widening of the Hadley circulation and whether the observed widening is related to anthropogenic forcing. In the present study, we use currently available simulations of the Coupled Model Intercomparison Project Phase-5 (CMIP5) to analyze changes in the width of the Hadley circulation. It is found that CMIP5 historical simulations with greenhouse gas (GHG) forcing generate a total widening of $\sim 0.15^\circ \pm 0.06^\circ$ in latitude $(10\ \text{yr})^{-1}$ for the period 1979–2005, and the widening in CMIP5 historical simulations with all forcings is $\sim 0.17^\circ \pm 0.06^\circ$ per decade. Similar to that in CMIP3, the simulated poleward expansion in CMIP5 is much weaker than the observational reanalyses. In CMIP5 projection simulations for the 21st century, magnitudes of widening of the Hadley circulation increase with radiative forcing. For the extreme projected radiative forcing of RCP8.5, the total annual-mean widening of the Hadley circulation is $\sim 0.27^\circ \pm 0.04^\circ$ $(10\ \text{yr})^{-1}$ in the 21st century. Although CMIP5 underestimates observed poleward expansion of the Hadley circulation, the results of this study suggest that the observed trends in the width of the Hadley circulation are caused by anthropogenic forcing and that increasing GHGs play an important role in the observed poleward expansion of the Hadley circulation, in addition to other forcings emphasized in previous studies.

Key words: global warming, Hadley circulation, increasing greenhouse gases, CMIP5

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1. Introduction

Observational analyses have shown that the Hadley circulation has undergone statistically significant poleward expansion in the past few decades (Hu and Fu, 2007). Using independent observational datasets, Hu and Fu (2007) found that poleward expansion of the Hadley circulation ranges from 2° to 5° in latitude since the late 1970s. They also found that the poleward expansion has large seasonal variations, that is, relatively large poleward expansion occurs in summer and autumn seasons in both hemispheres, while changes in the width of the Hadley circulation are weak and less significant in winter and spring seasons. Associated with poleward expansion of the Hadley circulation, the tropical belt has also demonstrated widening. Hudson et al. (2006) showed that the tropical belt of the ozone layer, which has lower concentration than that in the extratropics, expanded northward by $\sim 2.5^\circ$ during 1979–2005. Hu and Fu (2007) showed that the subtropical band of outgoing longwave radiation (OLR) underwent poleward expansion in both hemispheres in the 1980s and 1990s. Seidel and Randel (2008) and Lu et al. (2009) found that the width of the tropical tropopause, which has higher altitudes than the extratropical tropopause, also widened. Other datasets have also demonstrated widening of the tropical belt (Hu et al., 2011; Davis and Rosenlof,

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2012).

What caused the observed poleward expansion of the Hadley circulation? Using the Coupled Model Intercomparison Programme–Phase 3 (CMIP3) simulations for the 20th century, Son et al. (2009, 2010) found that models with prescribed ozone depletion generate greater poleward expansion of the southern Hadley cell during austral summer than models without prescribed ozone depletion. The result was confirmed by sensitivity tests with general circulation model (GCM) simulations (Polvani et al., 2011). They reasoned that Antarctic ozone depletion caused high-latitude cooling that extends to the troposphere and led to enhanced meridional temperature gradients between the tropospheric polar region and the extratropics. Consequently, a poleward shift of westerly winds and the southern Hadley cell in austral summer occurred. Allen et al. (2012) suggested that increasing black carbon aerosols and tropospheric ozone in the Northern Hemisphere (NH) mid-latitudes contributed to the observed poleward expansion of the northern Hadley cell during boreal summer. It is because both black carbon aerosols and tropospheric ozone absorbs solar radiation, which warms the extratropical troposphere and causes poleward shifts of the tropospheric subtropical jet stream and the northern Hadley cell. While these studies have suggested that increasing GHGs play a minor role in the widening of the observed poleward expansion of the Hadley circulation, other works have demonstrated that increasing GHGs are also important. Chen and Held (2007) showed that both tropospheric warming and polar stratospheric cooling are important in poleward expansion of the Hadley circulation. CMIP3 simulations for the 21st century demonstrated that global greenhouse warming will lead to widening of the Hadley circulation (Frierson et al., 2007; Lu et al., 2007).

In this short study, we use simulations from CMIP5 to investigate changes in the width of the Hadley circulation and to determine whether the changes are related to anthropogenic forcing.

2. Data and method

Datasets used here include CMIP5 simulations (Meehl et al., 2009; Moss et al., 2010; Taylor et al., 2012) and six reanalyses. For CMIP5 simulations, we use both historical simulations and future projection simulations for the 21st century. For historical simulations, we use three types of simulation data: historicalNAT, historicalGHG, and historical, which represent historical simulations from 1850 to 2005 with natural forcing, greenhouse gas (GHG) forcing, and all forcings, respectively. For projection simulations, we use data from the four scenarios of representative concentration pathways (RCPs): RCP2.6, 4.5, 6.0, and 8.5 W m^{-2}. CMIP5 models and simulations used here are listed in Table 1.

The six reanalysis datasets are (1) the European Center for Medium-Range Weather Forecast Reanalysis (ERA-Interim, Dee et al., 2011), (2) the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996; Kistler et al., 2001), (3) the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis

Table 1. CMIP5 models used in the present paper. Digital numbers in the table are ensemble simulations for each model. The last second row shows the numbers of ensemble members of models used in trend calculations.

Models	historicalNat	historicalGHG	historical	RCP2.6	RCP4.5	RCP6.0	RCP8.5
bcc-csm1-1	1		3	1	1	1	1
CanESM2	5	5	5	5	5		5
CCSM4	4	3	6	5	6	6	6
GFDL-CM3	3		5	1	1	1	1
GFDL-ESM2G			1	1	1	1	1
GFDL-ESM2M	1	1	1	1	1	1	1
GISS-E2-H	5	5	5				
GISS-E2-R	5	5	6	1	6	1	1
HadGEM2-ES	4	4	4	4	4	4	4
IPSL-CM5A-LR	3	3	6	3	4	1	4
IPSL-CM5A-MR			2	1	1	1	1
MIROC5			4	3	3	1	3
MIROC-ESM-CHEM	1		1	1	1	1	1
MIROC-ESM	1		3	1	1	1	1
MPI-ESM-LR			3	3	3		3
MRI-CGCM3	1		3	1	1	1	1
Model ensemble	12	7	16	15	15	13	15

(Kanamitsu et al., 2002), (4) the 20th-Century Reanalysis version 2 (20CR2) (Compo et al., 2011), and (5) the Japanese 25-year reanalysis (JRA-25) (Onogi et al., 2007). For both CMIP5 historical simulations and reanalyses, we use data for the period of 1979–2005. For CMIP5 projection simulations, the data are from the period 2006–2100.

The Hadley circulation is characterized using the mean meridional mass stream-function (MMS). Following the method in Hu and Fu (2007), we first locate poleward edges of the Hadley circulation, which are identified as the latitudes where MMS=0 kg s^{-1}. With this method, poleward expansion is estimated by calculating linear trends of the edge latitudes for each Hadley cell. The total expansion of the Hadley circulation is then obtained from the summation of the trends in these edge latitudes in both hemispheres. For each reanalysis dataset, statistical significance of the trend is estimated as the 95% confidence level using a standard t-test. For CMIP5 simulations, trend uncertainty is estimated from multi-model ensembles, as twice the standard error, $2 \times \sigma/\sqrt{n}$, where σ is the standard deviation of the trends and n is the number of trends (models).

3. Results

Figure 1a illustrates seasonal trends in poleward-edge latitudes of the northern Hadley cell, derived from three types of CMIP5 historical simulations for the period of 1979–2005. Trends vary with seasons. Simulations with natural forcing yield weak trends in December–February (DJF), March–May (MAM), and June–August (JJA), but relatively large trends in September–November (SON). Simulations with GHG forcing generate weak trends in DJF and JJA, but relatively large positive trends in MAM and SON. Especially in SON, the trend due to GHG forcing is the largest, with a magnitude of $\sim 0.2^\circ \pm 0.17^\circ$ (10 yr)$^{-1}$. This is roughly consistent with the seasonality of observed poleward expansion of the Hadley circulation, as shown in Hu and Fu (2007). The magnitudes of historical GHG trends are comparable to those in CMIP3 simulations. These results suggest that, in CMIP5 historical simulations, GHG forcing plays an important role in causing the observed poleward expansion of the northern Hadley cell.

Trends forced by all forcings are $0.02^\circ \pm 0.03^\circ$ (10 yr)$^{-1}$ (RCP2.6), $0.06^\circ \pm 0.07^\circ$ (10 yr)$^{-1}$ (RCP4.5), $0.06^\circ \pm 0.12^\circ$ (10 yr)$^{-1}$ (RCP6.0), and $0.04^\circ \pm 0.09^\circ$ (10 yr)$^{-1}$ (RCP8.5) (blue). These trends are much weaker than those reported by Allen et al. (2012), which showed trends of $\sim 0.14^\circ \pm 0.06^\circ$ (10 yr)$^{-1}$. It is difficult to interpret the differences in these trends at the current stage. Possibly, some models that do not include time-varying ozone and black carbon underestimate poleward expansion of the Hadley circulation; therefore, the ensemble mean yielded much weaker trends. These results require further detailed analysis as more simulation results with individual forcings are available.

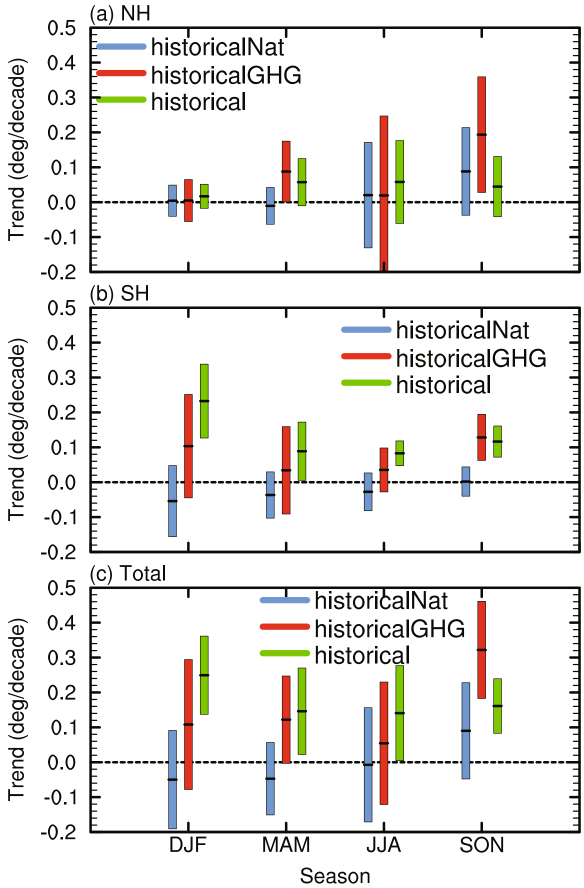

Fig. 1. Seasonal-mean poleward shifts of poleward edges of the Hadley circulation, derived from three CMIP5 historical simulations for the period of 1979–2005, averaged from 400 to 600 hPa. (a) The northern cell, (b) the southern cell, and (c) total poleward expansion. Positive trends indicate poleward shifts of the Hadley circulation and negative values indicate equator-ward shifts. Error bars are ±2 standard derivations, and it is the same for all other figures. Units are ° (10 yr)$^{-1}$.

For the southern Hadley cell (Fig. 1b), seasonal trends from simulations with natural forcing are either negative or close to zero, indicating that natural forcing does not cause poleward expansion of the southern Hadley cell. Trends from historical simulations with all forcings are generally greater than those from historical GHG simulations, except for SON, when the former is slightly weaker than the latter. In particular, the trend from simulations with all forcings is much greater than that from historical GHG simulations in austral summer (DJF). The magnitude of poleward expansion in DJF is $\sim$0.23°±0.11° (10 yr)$^{-1}$. On the one hand, poleward expansion of the southern Hadley cell in CMIP5 simulations is consistent with CMIP3 simulations (Son et al., 2009, 2010), that is, other forcings, such as ozone depletion in the stratospheric Antarctic, make important contributions to poleward expansion of the southern Hadley cell in austral summer. On the other hand, in CMIP5 simulations the DJF trend forced by GHG forcing alone is nearly half the trend forced by all forcings, i.e., 0.10° ± 0.15° (10 yr)$^{-1}$. Total seasonal poleward expansion of the Hadley circulation is shown in Fig. 1c. Trends from historical NAT simulations are negative in DJF, MAM, and JJA and positive in SON. In contrast, trends from historical simulations with GHG and all forcings are all positive. GHG forcing generate the largest total poleward expansion in SON, with a value of 0.32° ± 0.14° (10 yr)$^{-1}$. All forcings generate the largest total trend in DJF, with a value of $\sim$0.25°±0.11° (10 yr)$^{-1}$.

To compare trends between CMIP5 simulations and observational reanalyses, we plot annual-mean trends in total poleward expansion of the Hadley circulation of both datasets in Fig. 2a. Trends from five of the six reanalyses have values of $\sim$1.0° (10 yr)$^{-1}$, while JRA has the largest trend of $\sim$ 1.9° (10 yr)$^{-1}$. The reanalysis trends are statistically significant at the 95% confidence level, except for that from ERA-Interim, which has a much shorter period of only 17 years. The trend derived from CMIP5 historical NAT simulations is close to zero (red), suggesting that natural forcing do not cause widening or narrowing of the Hadley circulation in terms of the annual mean trend. Trends from CMIP5 historical simulations with GHG forcing and all forcings are $\sim$ 0.15° ± 0.07° and 0.17° ± 0.06° (10 yr)$^{-1}$ (green and blue), respectively. These simulated trends are approximately six times weaker than that in reanalyse.

Comparison of DJF poleward expansion the southern Hadley cell between reanalyses and CMIP5 is shown in Fig. 2b. Trends derived from reanalyses are all greater than 0.5° (10 yr)$^{-1}$, and the averaged value is $\sim$0.78° (10 yr)$^{-1}$. In contrast, trends forced by GHG and all forcings are 0.10°±0.15° and 0.23°±0.11° (10 yr)$^{-1}$, respectively. These suggest that CMIP5 simulations largely underestimate poleward expansion of the northern Hadley cell. It is the same for CMIP3 simulations (Johanson and Fu, 2009). Nevertheless, trends from CMIP5 historical simulations do suggest that the observed widening of the Hadley circulation is associated with anthropogenic forcing.

To further demonstrate how anthropogenic forcing

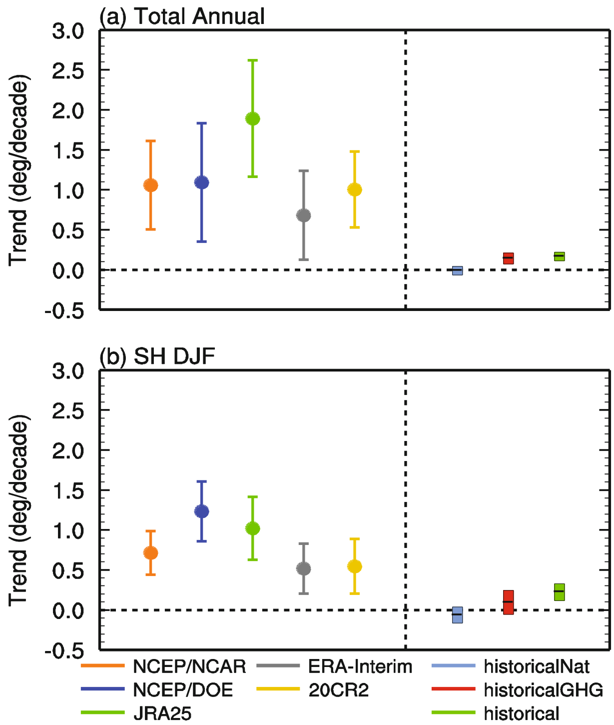

Fig. 2. Comparison of total poleward expansion of the Hadley circulation between reanalyses and CMIP5 historical simulations. (a) annual-mean total expansion of the Hadley circulation, and (b) poleward expansion of the southern Hadley cell in DJF. Units are ° (10 yr)$^{-1}$. All trends are calculated for the period of 1979–2005.

may cause poleward expansion of the Hadley circulation, we analyze trends from simulations with the four RCP scenarios of radiative forcing for the 21st century. Figure 3a shows seasonal trends for the northern Hadley cell. Trends increase with RCP forcing in general, except for JJA. The largest trends for the four scenarios all occurred in SON, with values of 0.04° ± 0.02° (10 yr)$^{-1}$ (RCP 2.6), 0.11° ± 0.04° (10 yr)$^{-1}$ (RCP4.5), 0.15° ± 0.05° (10 yr)$^{-1}$ (RCP6.0), and 0.25° ± 0.06° (10 yr)$^{-1}$ (RCP8.5) . Note that RCP2.6 represents a scenario with which radiative forcing peaks at about 2040, and then declines before 2100 (Moss et al., 2010). Time series show that the poleward edge of the northern Hadley cell in RCP2.6 simulations first demonstrate weak poleward expansion, and then show equatorward shifts (figure not shown here). This affects the linear trend calculation for RCP2.6 simulations for the period of 2006–2100. It also affects trends for RCP4.5 simulations, which also show equatorward shifts in the last decade of the 21st century. For RCP6.0 and RCP8.5 simulations, the poleward edge expands poleward systematically. Therefore, results from projec-

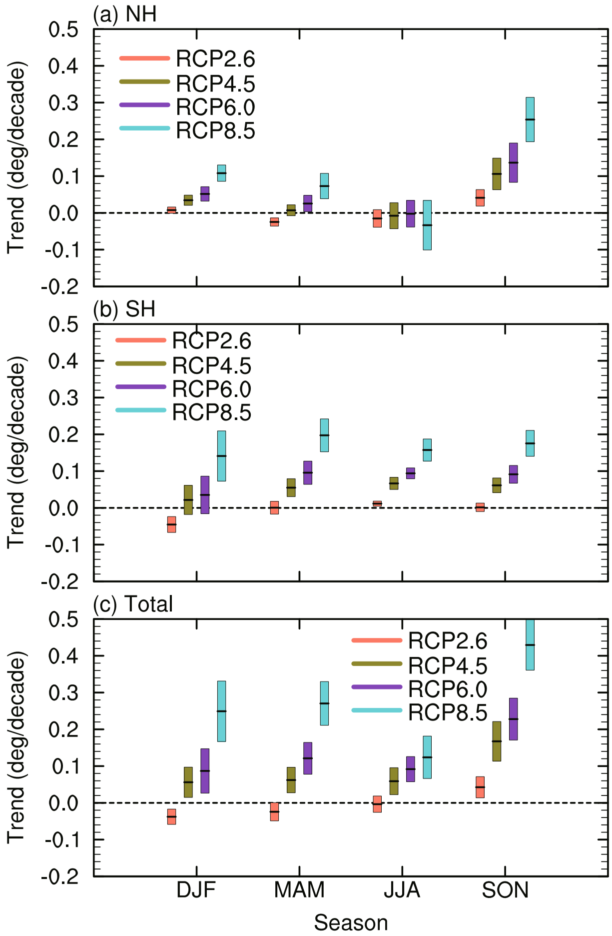

Fig. 3. Same as Fig. 1, except for CMIP5 RCP projection simulations. Trends were calculated for the period of 2006–2100, and the units of the trends are degrees $(10\ \mathrm{yr})^{-1}$.

tion simulations suggest that increasing GHGs will cause continuous poleward expansion of the northern Hadley circulation in the 21st century.

Similar to that of the northern Hadley cell, trend magnitudes in the width of the southern Hadley cell also increase with RCP forcings in all seasons (Fig. 3b). Trends from RCP2.6 simulations are either close to zero or negative for the reason addressed above. The largest trend is from RCP8.5 in MAM, with a value of $0.20° \pm 0.04°$ $(10\ \mathrm{yr})^{-1}$. Total seasonal poleward expansion of the Hadley circulation is shown in Fig. 3c. Trends increase with radiative forcing in all seasons. For all four RCP scenarios, the largest trends occurred in SON, with values of $0.04° \pm 0.03°$ $(10\ \mathrm{yr})^{-1}$ (RCP2.6), $0.17° \pm 0.05°$ $(10\ \mathrm{yr})^{-1}$ (RCP4.5), $0.24° \pm 0.06°$ $(10\ \mathrm{yr})^{-1}$ (RCP6.0), and $0.42° \pm 0.07°$ $(10\ \mathrm{yr})^{-1}$ (RCP8.5). The annual-mean total poleward expansion of the Hadley circulation for the four RCP scenarios is $-0.01° \pm 0.02°$ $(10\ \mathrm{yr})^{-1}$ (RCP2.6), $0.09° \pm 0.03°$ $(10\ \mathrm{yr})^{-1}$ (RCP4.5), $0.13° \pm 0.04°$ $(10\ \mathrm{yr})^{-1}$ (RCP6.0), and $0.27° \pm 0.04°$ $(10\ \mathrm{yr})^{-1}$ (RCP 8.5).

4. Conclusions

We studied poleward expansion of the Hadley circulation using CMIP5 historical and RCP projection simulations. Similar to CMIP3 and other previous GCM simulations, CMIP5 historical simulations generate much weaker trends in the width of the Hadley circulation than reanalysis observations over the past few decades. The simulated trends are approximately six times weaker than observations. It remains unknown why GCMs underestimate observed poleward expansion in the Hadley circulation.

Nevertheless, results from CMIP5 historical simulations suggest that anthropogenic forcing might be causing the observed poleward expansion of the Hadley circulation. CMIP5 simulations with natural forcing generate negative or weak trends in general. In contrast, historicalGHG simulations generate relatively large positive trends for the northern Hadley cell, especially in SON. Compared with previous results, GHG forcing in CMIP5 historical simulations seems to be more important in the observed widening of the Hadley circulation in recent decades. The role of GHG forcing is further demonstrated in RCP projection simulations, which show that the magnitude of poleward expansion of the Hadley circulation increases with RCP radiative forcing.

Historical simulations with all forcings generate the largest trend for the southern Hadley cell in DJF. This result is consistent with the observational seasonality of trends in the southern Hadley cell, indicating the influence of anthropogenic activity on the Hadley circulation. This result also suggests that Antarctic stratospheric ozone depletion, which is included in historical simulations with all forcings, had a significant influence on poleward expansion of the southern Hadley cell.

The results here are based on currently available CMIP5 simulations. As more simulation datasets are released, we plan to analyze trends in historical simulations with individual forcings. We also plan to analyze trends for projection simulations with more model results.

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