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Observational Evidence for Poleward Expansion of the Hadley Circulation

HU Yongyun*[1,3] (胡永云), ZHOU Chen[1] (周 晨), and LIU Jiping[2] (刘骥平)

[1] *Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing* 100871

[2] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Beijing,* 100029

[3] *Laboratory for Climate and Ocean-Atmosphere Studies, Peking University, Beijing* 100871

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ABSTRACT

How the Hadley circulation changes in response to global climate change and how its change impacts upon regional and global climates has generated a lot of interest in the literature in the past few years. In this paper, consistent and statistically significant poleward expansion of the Hadley circulation in the past few decades is demonstrated, using independent observational datasets as proxy measures of the Hadley circulation. Both observational outgoing longwave radiation and precipitation datasets show an annual average total poleward expansion of the Hadley cells of about 3.6° latitude. Sea level pressure from observational and reanalysis datasets show smaller magnitudes of poleward expansion, of about 1.2° latitude. Ensemble general circulation model simulations forced by observed time-varying sea surface temperatures were found to generate a total poleward expansion of about 1.23° latitude. Possible mechanisms behind the changes in the horizontal extent of the Hadley circulation are discussed.

Key words: Hadley circulation, outgoing longwave radiation, precipitation, sea level pressure, climate change

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1. Introduction

As one of the most prominent atmospheric circulations, the Hadley circulation must be affected by changes in the global climate. In turn, these affects must themselves impact upon regional and global climate. There has been a growing interest in decadal-scale changes to the Hadley circulation in recent years, with studies tending to focus on two aspects: decadal-scale changes in the intensity of the Hadley circulation, and its horizontal extent.

Using outgoing longwave radiation (OLR) datasets from the Earth Radiation Budget Experiment, Chen et al. (2002) and Wielicki et al. (2002) reported increasing OLR in the subtropics. Both groups of authors suggested that this increase in subtropical OLR is indicative of an intensification of the Hadley circulation in the 1980s and 1990s because an intensified Hadley circulation would lead to stronger descending motion in the subtropics in both hemispheres, and thus cause greater emissions of infrared radiation into space. Using reanalysis datasets, Hu et al. (2005) and Mitas and Clement (2005) concluded that the winter cell of the Hadley circulation has experienced significant intensification in the past few decades. However, it was later found that the increase in OLR underpinning these studies was due mainly to a significant decline in satellite altitudes (Wong et al., 2006). In a later paper, Mitas and Clement (2006) themselves also wrote of the intensification of the Hadley circulation in reanalysis datasets possibly being due to artificial reasons. Therefore, whether or not the Hadley circulation has intensified in recent decades remains a controversial issue.

*Corresponding author: HU Yongyun, yyhu@pku.edu.cn

In terms of decadal-scale changes in the horizontal extent of the Hadley circulation, recent studies have produced evidence that the Hadley circulation has perhaps extended poleward during the last few decades. For example, using satellite-based microwave sounding unit (MSU) data, Fu et al. (2006) showed an enhanced warming in the mid-latitude troposphere, indicating poleward shifts of subtropical jet streams. Since the location of the subtropical jet stream marks approximately the poleward edge of the Hadley circulation, the authors suggested that the results could mean a poleward expansion of the Hadley circulation by about 2° latitude. Using reanalysis datasets, Hu and Fu (2007) calculated zonal-mean meridional mass streamfunction and showed direct evidence of poleward expansion of the Hadley circulation since 1979. They also used three independent OLR datasets to confirm the results. Both the reanalysis and OLR datasets suggested a total poleward expansion of about 4° latitude. Hu and Fu (2007) also demonstrated that the poleward expansion of the Hadley circulation, as evidenced from the reanalysis data, displays seasonality. They found that, in both hemispheres, a large and statistically significant poleward expansion occurs mainly in summer and autumn, whereas trends are relatively weak and less significant in winter and spring.

Poleward expansion of the Hadley circulation implies a widening of the tropical belt, which distinguishes the tropics from the extratropics in terms of climatological features. Accordingly, instead of dealing directly with changes in the Hadley circulation, several recent works have focused on other measures aimed at showing a widening of the tropical belt (Seidel et al., 2008). Using observed total column ozone data, Hudson et al. (2006) showed that the lower-stratospheric tropical belt, which has a lower concentration of ozone than the extratropics, extended poleward in the Northern Hemisphere (NH) by about 2.5° latitude since 1979. Using radiosonde and reanalysis data, Seidel and Randel (2007) showed that the tropical tropospause, which has relatively high altitudes, extended toward the extratropics in both hemispheres by a total of about 5°–8° latitude during the period 1979–2005. In addition, subtropical jet streams in both hemispheres have been shown to have shifted poleward during the past few decades (Seidel et al., 2008). All of the results reported in these studies are consistent with the likely poleward expansion of the Hadley circulation.

However, in spite of this, the reported magnitude of the poleward expansion, as well as the seasonal variation, has differed from study to study. Specifically, the magnitude has varied from about 2° latitude in MSU data, to 8° for tropopause heights from reanalysis data. Moreover, simulation results from GCMs have also shown poleward expansion of the Hadley circulation (Lu et al., 2007; Johanson and Fu, 2009; Hu and Zhou, 2009). However, all such simulations have yielded a much weaker poleward expansion compared with observations. Using the Intergovernment Panel on Climate Change/Fourth Assessment Report (IPCC-AR4) simulations, Lu et al. (2007) showed a poleward expansion of about 1° latitude for the 21st century. Johanson and Fu (2009) and Hu and Zhou (2009) found that poleward expansion of the Hadley circulation in the last 20 years of the 20th century to be generally less than 1°. This suggest that further studies which use more observational and modeling datasets are necessary to confirm decadal-scale changes in the horizontal extent of the Hadley circulation or the tropical belt. The main goal for the present study, therefore, was to provide more evidence for the poleward expansion of the Hadley circulation through the use of additional, independent datasets.

The datasets used in the study are described in section 2. Results are presented in section 3, in trends in OLR, precipitation, sea level pressure (SLP), and zonal-mean mass streamfunction are shown, as derived from AGCM simulations forced with observed time-varying SST. A discussion and conclusions are presented in section 5.

2. Data and method

Datasets used in this study include: monthly OLR, precipitation, SLP, and GCM ensemble simulations. The OLR data were from the NOAA (National Ocean and Atmosphere Administration), interpolated on grids of 2.5°×2.5° latitude and longitude (Liebmann and Smith, 1996). The NOAA OLR data are not completely independent from those used in Hu and Fu (2007), since some OLR records are from the same satellite observations. They do, however, have different calibration and validation methods applied (Liebmann and Smith, 1996). The precipitation data were from the Global Precipitation Climatology Project (GPCP), which was designed to provide improved long-term estimates of precipitation over the globe (Huffman et al., 2001; Adler et al., 2003). Four SLP datasets were used: three reanalysis datasets (the European Centre for Medium-Range Weather Forecasts (ERA40) (Uppala et al., 2005), the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996), and the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) (Kanamitsu et al., 2002), and one near real-time product from the Hadley Centre of the Meteorological Office

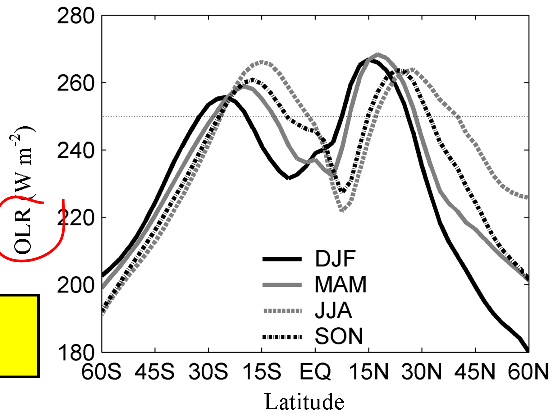

Fig. 1. Zonal mean OLR climatology averaged over the period 1979–2009.

(HadSLP2) (Allan and Ansell, 2006). The three reanalysis datasets are all on grids of 2.5°×2.5° latitude and longitude, whereas HADSLP2 has a lower resolution, at 5°×5°. All observational and reanalysis data covered the period March 1979 to February 2009 (30 years), except for ERA40 which was from March 1979 to February 2002 (24 years). In addition to these data, simulation results from NCAR-CAM2 (Kiehl et al., 1998) were also used, with 12 ensemble numbers of simulations. The model was integrated from 1871–2002 and forced by observed time-varying SST alone. To compare with observations, linear trend analysis for the model limited over the period from 1979–2002 (24 years) only.

3. 3. Results

3.1 *Trends in OLR*

Figure 1 shows seasonal zonal mean OLR climatology averaged over the period 1979–2009 (hereafter, winter, spring, summer, and autumn will be denoted by DJF, MAM, JJA, and SON, respectively). The zonal-mean climatological OLR peaks in the subtropics in both hemispheres, with seasonal variations of locations in the meridional direction. The high values of OLR in the subtropics is because of the dryness and lack of clouds caused by subtropical descending motion associated with the subsidence branch of the

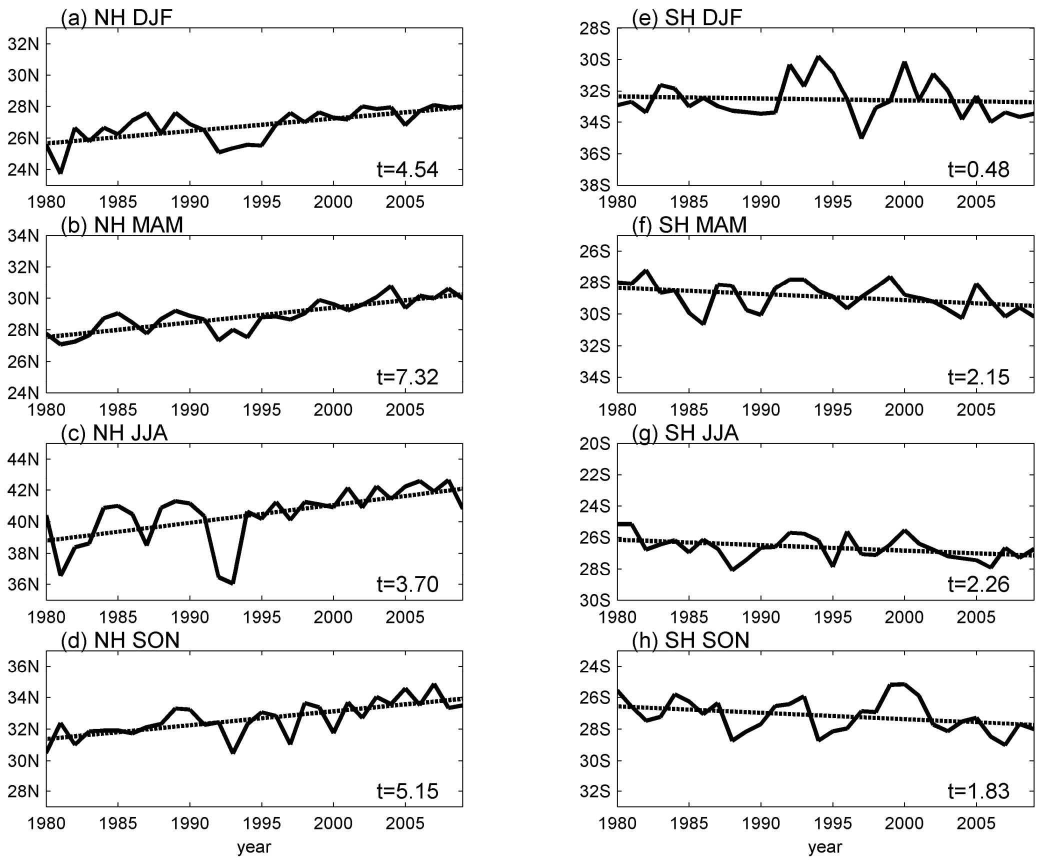

Fig. 2. Time series of the poleward latitudes at which the seasonal and zonal mean OLR is equal to 250 W m^{-2}. Left panel: NH; right panel: SH. From top to bottom, the plots are for DJF, MAM, JJA, and SON, respectively. Straight dashed-lines show linear trend plots.

Hadley circulation. Therefore, the subsidence branch of the Hadley circulation can be identified as the region with high OLR in the subtropics. Comparison between zonal-mean mass streamfunction and zonal-mean OLR shows that the poleward location (latitude) of OLR with a value of 250 W m^{-2} matches approximately the poleward edge of the Hadley circulation. Thus, the poleward latitudes where the zonal-mean OLR equals 250 W m^{-2} are defined as the locations of the poleward edges of the Hadley circulation, following Hu and Fu (2007). The latitude of the 250 W m^{-2} OLR was obtained by linear interpolation. Note that one can also use other OLR values, such as 260 or 240 W m^{-2}, as the edge of the Hadley circulation, and results remain almost the same.

Figures 2a–d show time series of the poleward latitude of OLR with a seasonal-mean value of 250 W m^{-2} in the NH over the period 1979–2009. For all four seasons, the time series show systematic northward shifts. The net poleward shift over the 31 years is 2.36°, 2.67°, 3.35°, and 2.43° latitude for the four seasons, respectively, with statistical confidence levels all above 95%. Figures 2e–h show the time series of the poleward latitude of seasonal 250 W m^{-2} OLR in the Southern Hemisphere (SH) over the period 1979–2009. Again, as with the NH, significant poleward shifts of the time series can be seen in MAM, JJA and SON, the exception being in DJF where the shift is relatively weak and statistically insignificant.

Net poleward shifts in the seasonal mean latitudes of 250 W m^{-2} OLR in both hemispheres are summarized in Fig. 3. In general, poleward shifts in OLR show no significant seasonality in both hemispheres, unlike mass streamfunction which has significant poleward expansion in both hemispheres, but in summer and autumn only (Hu and Fu, 2007). From Fig. 3, one can also see that poleward shifts in OLR are greater in the NH than in the SH. In terms of the annual average, net poleward shift in OLR in the NH is about 2.70° latitude over the 30 years, whereas in the SH the shift is much weaker, at about 0.78°. Total poleward shift for both hemispheres (the sum of shifts in both hemispheres) is about 3.48° latitude. This is comparable to in the results of Hu and Fu (2007), in which three OLR datasets (HIRS, ISSCP, and GEWEX) yielded net total annual-mean poleward shifts of 4.5°, 4.0°, and 2.3° latitude, respectively.

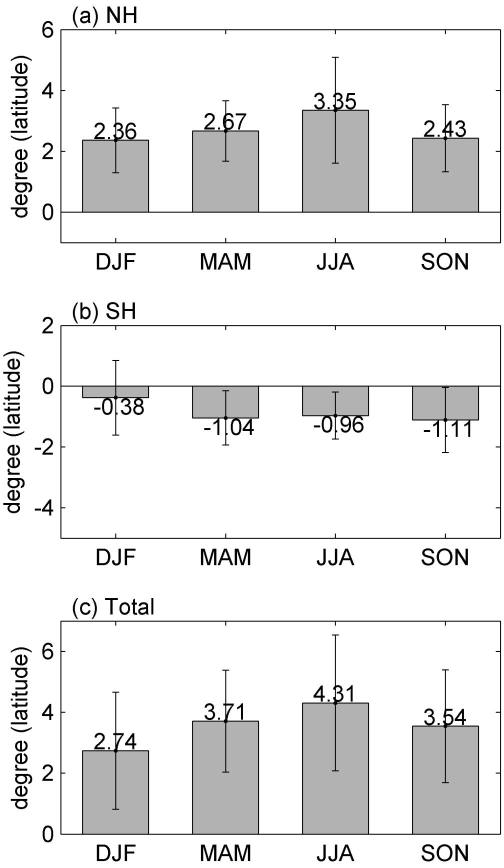

Fig. 3. Net poleward shifts of the latitude with 250 W m^{-2} OLR: (a) NH; (b) SH; and (c) total (NH minus SH trends). Positive values indicate northward shift, and negative values southward.

3.2 *Trends in precipitation*

It is well known that the subtropics experience relatively lower levels of precipitation due to subsidence of the Hadley circulation. As the Hadley circulation expands poleward, the subtropical dry zone must thus be extended toward the extratropics in both hemispheres. Therefore, the location of the subtropical dry zone can be considered a proxy for the subsidence branch of the Hadley circulation. It was shown in recent work that precipitation in the NH subtropics has been declining in the past few decades (Zhang et al., 2007). However, the study did not look at the possible poleward expansion of the subtropical dry zone. Here, GPCP observational precipitation data was used to assess whether there has been poleward expansion of the subtropical dry zone and, if so, whether the change is consistent with that of the Hadley circulation in other datasets. The latitude with minimum zonal-mean precipitation in the subtropics, which is located using the cubic spline interpolation method, was chosen to represent the location of the dry zone.

Figure 4 shows trends in seasonal and zonal mean GPCP precipitation over the period 1979–2009 (black),

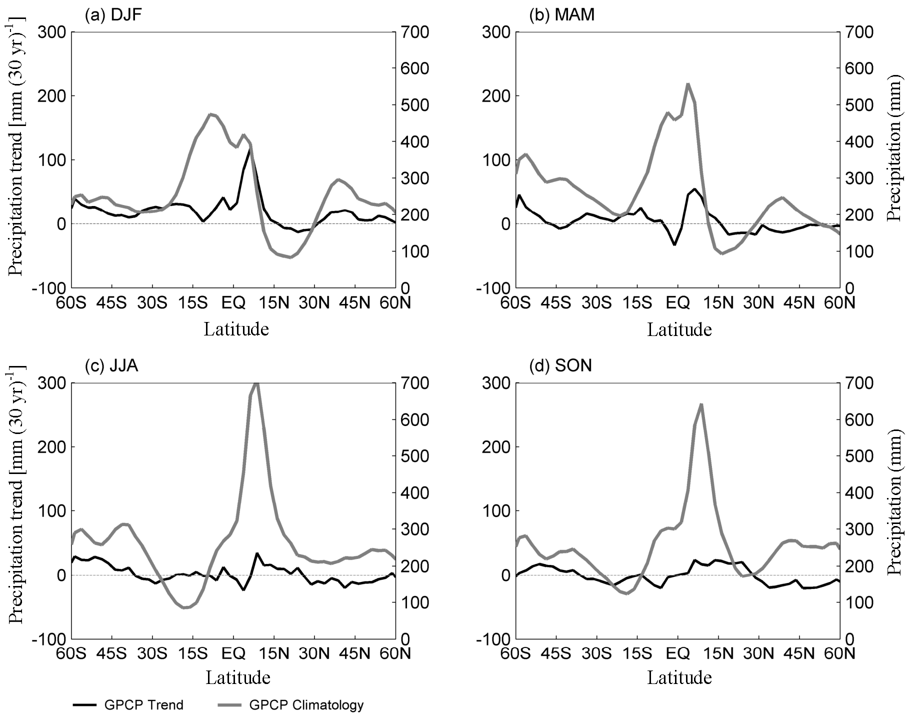

Fig. 4. Trends in seasonal and zonal mean GPCP precipitation over the period 1980–2007 (black lines). Seasonal and zonal mean climatological precipitation (gray lines) is also plotted to show the meridional distribution of precipitation. The left y-axis is for trends, and the right y-axis for climatology.

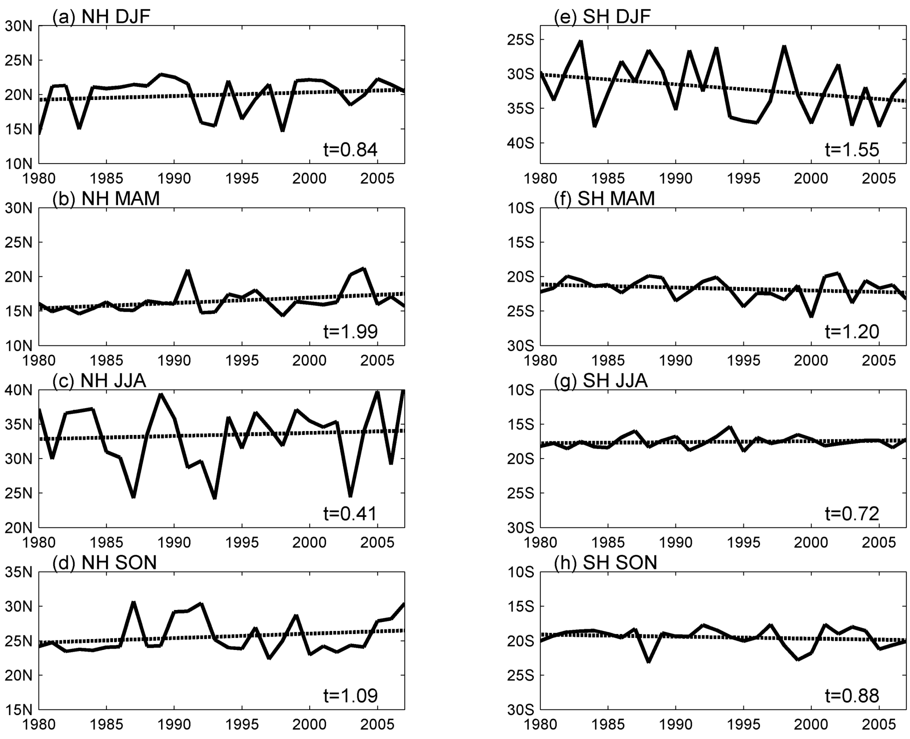

Fig. 5. Time series of the minimum-precipitation latitude in the subtropics. Left panel: NH; right panel: SH. From top to bottom, the plots are for DJF, MAM, JJA, and SON, respectively.

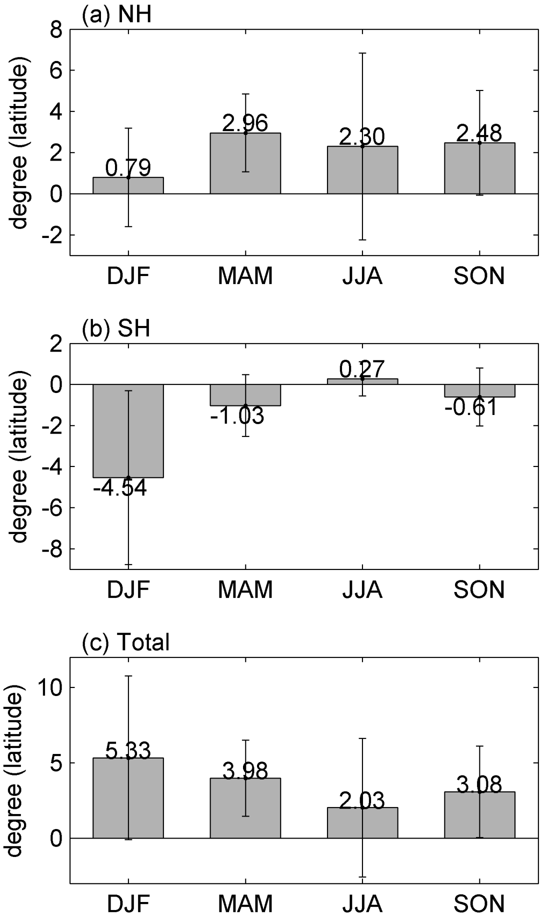

Fig. 6. Net poleward shifts of the minimum-precipitation latitude: (a) NH; (b) SH; and (c) total.

overlapped with seasonal and zonal mean climatological precipitation (gray lines) averaged over the same period. It is obvious that climatological precipitation has maximum values in the tropics and two minima in the subtropics in all four seasons, and the subtropical minima show seasonal variation in their location. Trends in precipitation generally show negative values in the subtropics for all four seasons, especially in the NH, indicating a reduction in precipitation in this region, while trends in the tropics and high latitudes are generally positive. It is particularly important to note that the locations of the largest negative trends are generally more poleward compared with the locations of climatological minimum precipitation in the subtropics. This is indicative of the poleward expansion of the subtropical dry zone.

Figure 5 shows the temporal evolution of minimum-precipitation latitudes in both hemispheres for the four seasons. For the NH (Figs. 6a–d), a poleward shift in all seasons is apparent. The trend in MAM has the greatest statistical significance, above the 98% confidence level, and the trend in SON has significance above the 80% confidence level. The trends in DJF and JJA on the other hand, are statistically insignificant. For the SH, a statistically significant southward shift is found only for austral summer (DJF), which also has the largest southward shift. Trends in the other three seasons are weak and statistically insignificant.

Net poleward shifts of minimum-precipitation latitude over the 30 years are summarized in Fig. 6. In the NH, trends do not display significant seasonal variation, and the annual-mean shifts poleward by about 2.13° latitude. In the SH, the trend in DJF is large, about $-4.54°$ latitude (southward), with the other three seasons showing trends of less than 1.0°. The annual average is about 1.56°, and the total annual-mean poleward expansion is about 3.69°.

3.3 *Trends in sea level pressure*

The Hadley circulation transports air mass from the tropics to the subtropics, causing low SLP over the tropics and high SLP over the subtropics. The latter is the so called subtropical high. The zonal-mean SLP maximum corresponds to the zero point of the zonal-mean meridional winds near the surface. Considering that the streamlines are close to vertical above the boundary layer, the zero points of zonal-mean meridional winds correspond to the zero streamline that separates the Hadley and Ferrel cells. Thus, the latitude of the maximum SLP marks approximately the poleward edge of the Hadley circulation. Therefore, the latitude corresponding to the maximum subtropical SLP was chosen to indicate the meridional extension of the Hadley circulation. The maximum-SLP latitude was located using the cubic spline interpolation method.

Figure 7 shows trends in seasonal and zonal mean SLP from four different datasets over the period 1979–2009 and the averaged zonal-mean climatological SLP from NCEP/NCAR, NCEP/DOE, and HadSLP2 over the same period. The climatological SLP shows that the location of the maximum SLP in the subtropics varies between about 30° and 40° latitude from one season to another for both hemispheres, matching approximately the poleward edge of the Hadley circulation. In general, positive trends are found at the poleward sides of climatological subtropical highs, indicating poleward shifts of subtropical highs in both hemispheres, except for those in the NH in JJA and MAM.

The NCEP/DOE SLP was taken as an example to demonstrate the temporal evolution of the maximum-SLP latitudes (Fig. 8). For the NH, the largest and most statistically significant poleward shift of the

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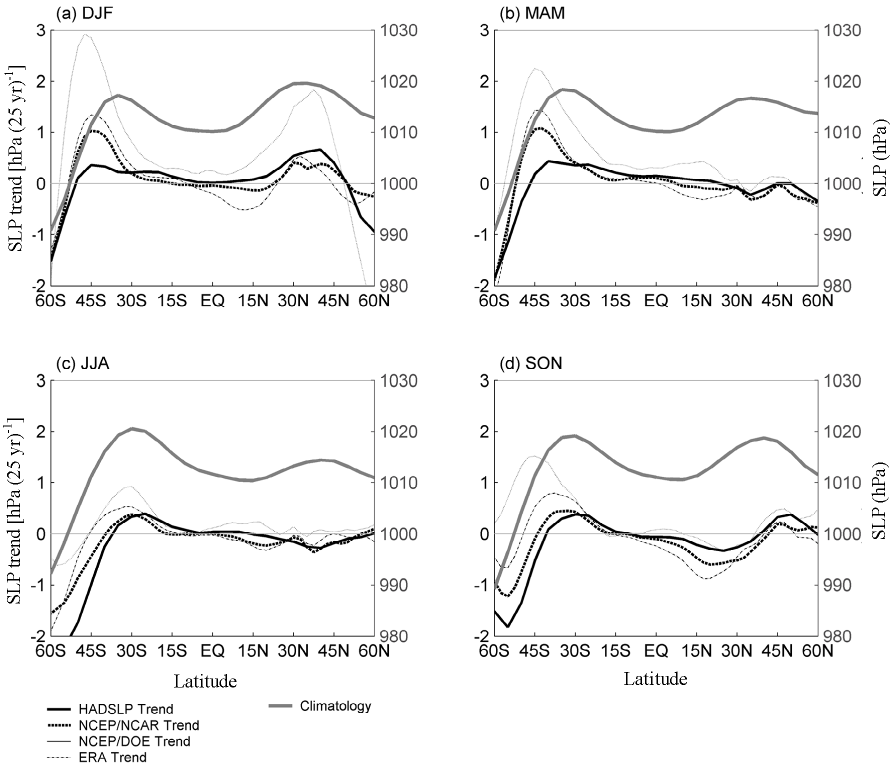

Fig. 7. Trends in annual and zonal mean SLP over the period 1980–2007. SLP trends from different datasets are marked with different styles of lines, as shown in the plots. Climatological zonal-mean precipitation is also plotted (thick gray line). The left y-axis is for trends, and the right y-axis for climatology.

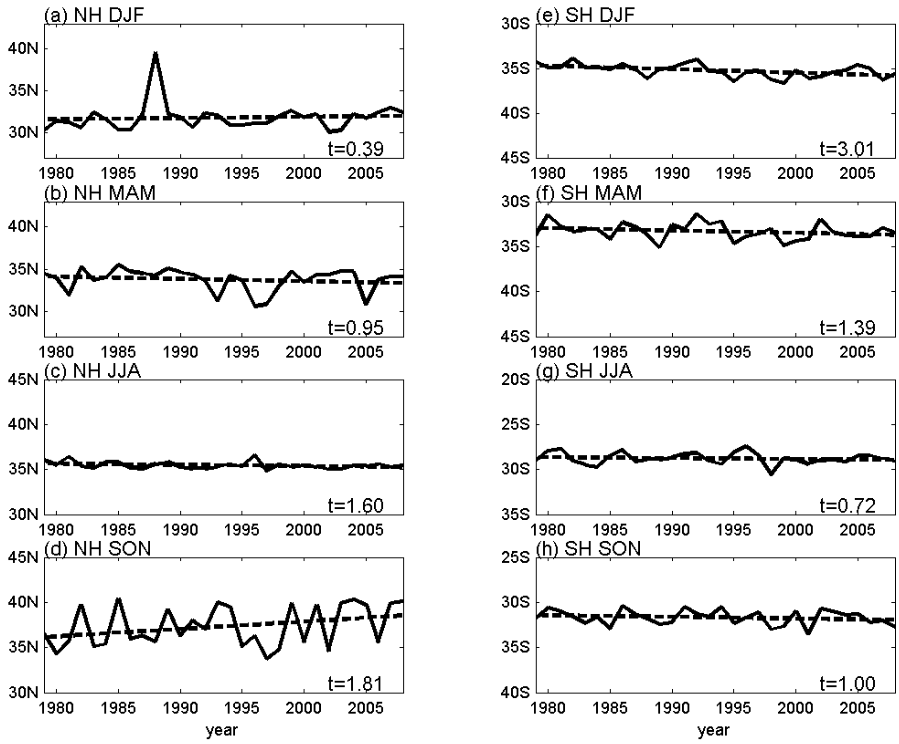

Fig. 8. Time series of the maximum-SLP latitudes in the subtropics, derived from NCEP/DOE reanalysis data. Left panel: NH; right panel: SH. From top to bottom, the plots are for DJF, MAM, JJA, and SON, respectively.

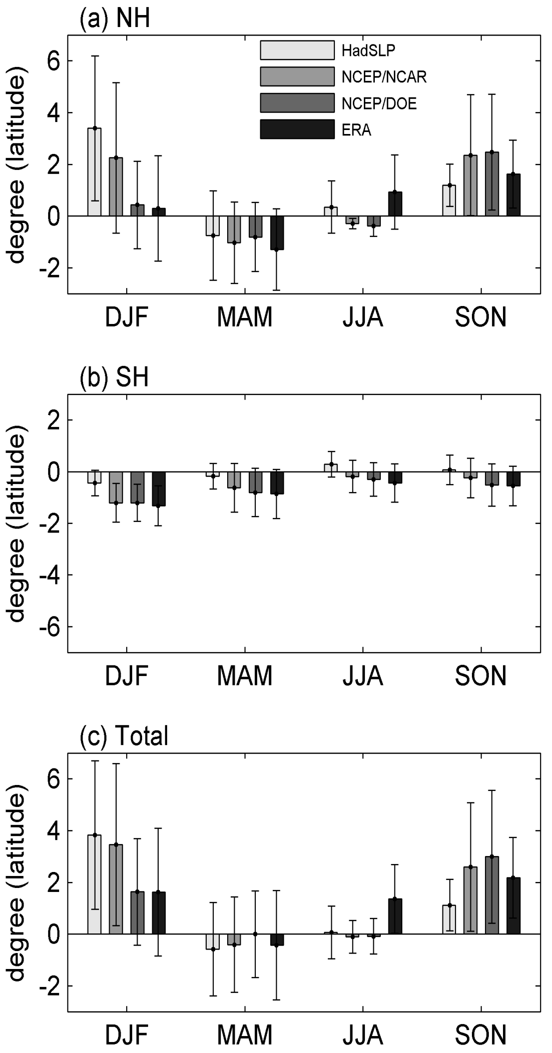

Fig. 9. Net poleward shifts of the maximum-SLP latitude: (a) NH; (b) SH; and (c) total.

maximum-SLP latitude is in SON. Trends in DJF and MAM are weak and insignificant, and the trend in JJA has a small negative value. For the SH, the largest and most statistically significant trend is found in DJF, with the trend in MAM showing significance above the 80% confidence level. Trends in JJA and SON are weak and insignificant.

Net poleward shifts of the maximum-SLP latitude are summarized in Fig. 9. In the NH, all four datasets yield relatively large poleward shifts in DJF and SON, with trends in MAM being negative (equatorward shift), but not significant. Trends in JJA have negative values and are relatively weak and statistically insignificant. In the SH, trends in the four datasets are generally poleward (negative), except for those from HadSLP2 which shows very weak equatorward shifts in JJA and SON. Total poleward shifts are large in DJF and SON and relatively weak in MAM and JJA. Averaged values of total poleward shifts for the four datasets are 2.70° and 2.28° latitude for DJF and SON, respectively. Annual-mean total poleward expansion is about 1.21°.

3.4 *Modeling results*

For the model simulations, zonal mean mass streamfunction was used to characterize the Hadley circulation. It was found that the climatological Hadley circulation produced by CAM2 is a close approximation to that of the NCEP/NCAR reanalysis dataset, both in strength and meridional extension (figures not shown). Following Hu and Fu (2007), the locations of the poleward edges of the Hadley circulation were identified as the latitude where mass streamfunction equals 0 kg s^{-1}. The latitude was located using linear interpolation. Figure 10 shows the time series of seasonal-mean poleward-edge latitudes of the Hadley circulation in both hemispheres. For the NH, the Hadley circulation displays systematic poleward expansion in all four seasons. Trends in JJA and SON are statistically significant at a confidence level of greater than 95%. Trends in DJF and MAM are statistically insignificant. For the SH, a significant trend can be seen only in austral autumn (MAM), with the other three seasons showing very weak and insignificant trends.

Net poleward expansion of the Hadley circulation in the simulations is summarized in Fig. 11. In the NH, trends in JJA and SON are relatively strong and statistically significant, while trends in DJF and MAM are weak and insignificant. This is consistent with trends from reanalysis data (Hu and Fu, 2007), in which the northern cell shows significant and large poleward expansion in boreal summer and autumn. The annual average of the NH trends is about 0.84° latitude over the period 1979–2002. Extrapolation of the 24-year trend to 30 years yields a value of about 1.05°, which is still less than one half of the trends found in reanalysis data. In the SH, a significant and large trend can be seen only in austral autumn (MAM), with all other seasons showing extremely weak and insignificant trends. The total annual poleward expansion is about 1.21° latitude, much smaller than that in the reanalysis data (about 2.4°).

4. Discussion and conclusions

This paper has examined independent observational datasets, including OLR, precipitation and SLP, to demonstrate poleward expansion of the Hadley circulation. Annual mean trends from these datasets are summarized in Table 1. A general consistent pattern

Table 1. Annual averages of hemispheric and total poleward expansion of OLR, precipitation, SLP, and simulated mass streamfunction. Units: degrees latitude. For hemispheric trends, positive values indicate northward expansion, and negative values southward. Trends in simulated mass streamfunction are linearly extrapolated to 30 years for comparison.

	NH	SH	Total
OLR	2.70°	− 0.78°	3.48°
Precipitation	2.13°	− 1.56°	3.69°
SLP	0.67°	− 0.54°	1.21°
Simulated streamfunction	1.05°	− 0.18°	1.23°

among these datasets is that they all demonstrate poleward expansion of the Hadley circulation, but with different magnitudes. Trends in OLR and precipitation data show total poleward expansion of about 3.6° latitude, which is comparable to the results of Hu and Fu (2007). By contrast, annual-mean trends in SLP demonstrate a smaller poleward expansion of about 1.21° latitude, close to that derived from MSU data (Fu et al., 2006). Trends in both OLR and precipitation show interhemispheric asymmetry, with a larger poleward expansion in the NH than the SH. For SLP, such asymmetry could only be found in DJF and SON.

Although these independent observational datasets show consistent poleward expansion of the Hadley circulation, what caused it remains an open question. Theories exist which predict that the Hadley cells with conserved angular momentum terminate at the latitude where baroclinic waves begin to take place (Held and Hou, 1980; Held, 2000). Thus, weakening or a poleward shift of baroclinic waves may cause poleward expansion of the Hadley circulation. Dynamical diagnostics from observations and model simulations have suggested that changes in atmospheric thermal structures and tropical SSTs due to external radiative forcing cause weakening and a poleward shift of baroclinic waves, which consequently causes poleward expansion of the Hadley circulation (Fu et al., 2006; Lu et al., 2007; Hu and Fu, 2007; Chen and Held, 2007; Frierson et al., 2007; Lu et al., 2008; Son et al., 2008; Son et al., 2009; Johanson and Fu, 2009; Lu et al., 2009). Lu et al. (2007, 2008) pointed out that global warming due to increasing greenhouse gases leads to a greater

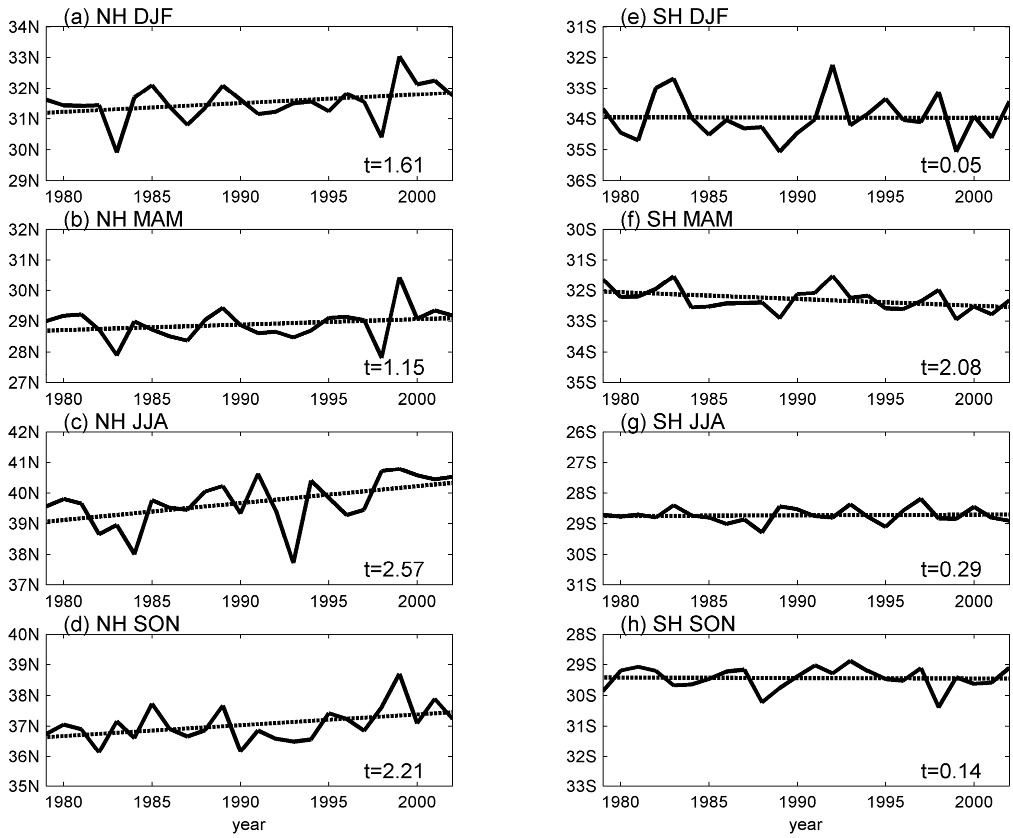

Fig. 10. Time series of the latitudes where mass streamfunction = 0 kg s^{-1}, derived from ensemble simulations. Left panel: NH; right panel: SH. From top to bottom, the plots are for DJF, MAM, JJA, and SON, respectively.

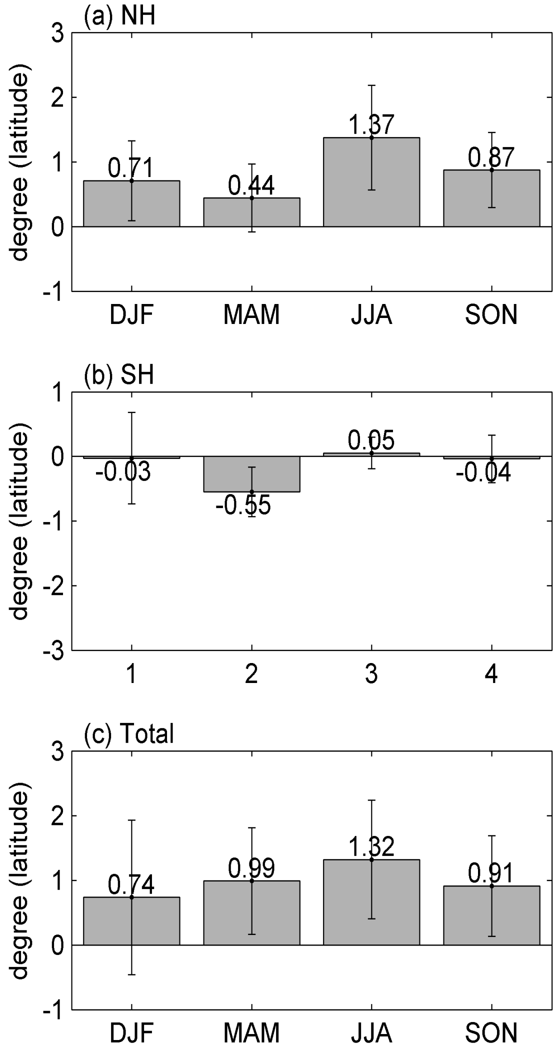

Fig. 11. Net poleward expansion of the Hadley circulation: (a) NH; (b) SH; and (c) total.

rate of warming in the upper troposphere than at lower levels, as a result of quasi-moist adiabatic adjustment. This causes increases in static stability and thus a reduction of baroclinic wave activity in the subtropics and extratropics. Chen and Held (2007) and Chen et al. (2008) suggested that tropospheric warming due to increasing greenhouse gases and stratospheric cooling due to both ozone depletion and increasing greenhouse gases lead to enhanced meridional temperature gradients around the tropopause and thus stronger westerly winds. The increase in westerly zonal winds accelerates eastward phase speeds of baroclinic waves, shifting subtropical waves breaking poleward and consequently causing poleward expansion of the Hadley circulation. The radiative forcing of ozone changes was particularly emphasized by Son et al. (2008, 2009). They showed, using GCM simulations, that ozone depletion in the last 20 years of the 20th century made a significant contribution to the poleward expansion of the Hadley circulation, and that ozone recovery in the 21st century will likely decelerate the tendency. However, results in the present paper have not shown a slow-down in poleward expansion in recent decades, when stratospheric ozone has shown stabilization or a weak increase.

As an integral part of global warming, increasing tropical SSTs are of great importance in causing poleward expansion of the Hadley circulation, as pointed out by Frierson et al. (2007), Lu et al. (2008), and Johanson and Fu (2009). These studies all suggested that SST warming over a broad tropical region tends to cause poleward expansion of the Hadley circulation, whereas SST warming over a narrow tropical region around the equator, with an El-Niño-like SST pattern, leads to a shrinking of the Hadley circulation. Indeed, GCM simulations with observed time-varying SST forcing, as shown in Figs. 10 and 11, generate poleward expansion of the Hadley circulation. In particular, simulations demonstrate similar seasonality to that in reanalysis data (Hu and Fu, 2007); that is, a significant poleward expansion is found mainly in summer and autumn in both hemispheres. Similar results have also been reported based on multi-model ensemble simulations with observed SST forcing (Hu and Zhou, 2009). However, simulated magnitudes of poleward expansion with SST forcing are all weaker than in reanalysis data. This raises the question of whether SST forcing alone can reproduce observed poleward expansion of the Hadley circulation. Moreover, simulation results reported by Lu et al. (2009) suggested that widening of the tropics over the period 1958–1999,

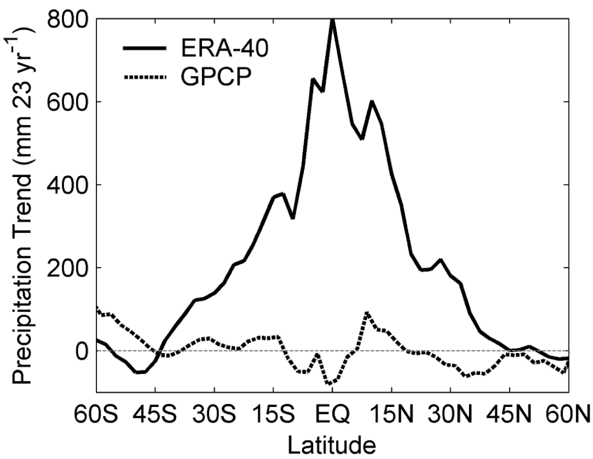

Fig. 12. Comparison of annual and zonal mean trends in precipitation between GPCP and ERA40 data over the period 1979–2001.

based on frequencies of daily tropical tropopause, is mainly caused by radiative forcing due to increasing greenhouse gases and stratospheric ozone depletion, and that SST forcing has no significant influence on the widening of the tropics. Although their results do not necessarily contradict the simulated results in the present paper, since they focused on different quantities over different periods, it suggests that detailed studies are needed to examine the relative importance of SST forcing on the poleward expansion of the Hadley circulation.

Theoretically, coupled atmospheric and oceanic GCM simulations, which include changes in both SSTs and atmospheric thermal structures, would better reproduce observed poleward expansion. However, magnitudes from coupled GCM simulations are even weaker than those in atmospheric GCMs forced with SST alone (Lu et al., 2007; Johanson and Fu, 2009). Therefore, whether the discrepancy between observations and simulations is due to model capability or other reasons remains unanswered and requires further investigation.

Before concluding the paper, it is worthwhile using Fig. 12 to make a brief comment on the strengthening of the Hadley circulation in the reanalysis data. Mitas and Clement (2005) found significant intensification of the Hadley circulation from NCEP/NCAR and ERA40 reanalyses. In later work, they showed that the intensification of the Hadley circulation in NCEP/NCAR reanalysis data is associated with weak cooling trends in the tropical middle troposphere, which was considered an artificial result caused by the switch of radiosonde instruments (Mitas and Clement, 2006). Thus, the authors suggested that the intensification of the Hadley circulation in NCEP/NCAR reanalysis data is artificial. However, what caused the intensification in the ERA40 reanalysis data was not discussed in their paper. In Fig. 12, annual and zonal mean precipitation trends between GPCP and ERA40 data over the period 1979–2001 are compared. While GPCP precipitation (observation) shows weak negative trends around the equator, ERA40 reanalysis data displays large positive trends in tropical precipitation, with a maximum value of 800 mm over the 23 years right over the equator. This strong contrast suggests that the large increase in tropical precipitation in the ERA40 data may not be realistic. Therefore, the intensification of the Hadley circulation in the ERA40 reanalysis may not be realistic. Instead, it is likely due to artificially increased tropical precipitation that is accompanied with an unrealistically enhanced upward motion.

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REFERENCES

Adler, R. F., and Coauthors, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). *J. Hydrometeor.*, **4**, 1147–1167.

Allan, R. J., and T. J. Ansell, 2006: A new globally complete monthly historical mean sea level pressure data set (HadSLP2): 1850–2004. *J. Climate*, **19**, 5816–5842.

Chen, J. Y., B. E. Carlson, and A. D. Del Genio, 2002: Evidence for strengthening of the tropical general circulation in the 1990s. *Science*, **295**, 838–841.

Chen, G., and I. M. Held, 2007: Phase speed spectra and the recent poleward shift of Southern Hemisphere surface westerlies. *Geophys. Res. Lett.,* **34,** L21805, doi: 10.1029/2007GL031200.

Chen, G., J. Lu, and D. M. W. Frierson, 2008: Phase speed spectra and the latitude of surface westerlies: Interannual variability and global warming trend. *J. Climate,* **21,** 5942–5959.

Frierson, D. M. W., J. Lu, and G. Chen, 2007: The width of the Hadley cell in simple and comprehensive general circulation models. *Geophys. Res. Lett.*, **34**, L18804, doi: 10.1029/2007GL031115.

Fu, Q., C. M. Johanson, J. M. Wallace, and T. Reichler, 2006: Enhanced mid-latitude tropospheric warming in satellite measurements. *Science*, **312**, 1179.

Held, I. M., 2000: The general circulation of the atmosphere. Proc. 2000 Program in Geophysical Fluid Dynamics. Woods Hole, MA, Woods Hole Oceanographic Institute, 1–54. [Available online at http://gfd.whoi.edu.]

Held, I. M., and A. Y. Hou, 1980: Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Res.,* **37,** 515–533.

Hu, Y., and Q. Fu, 2007: Observed poleward expansion of the Hadley circulation since 1979. *Atmos. Chem. Phys.*, **7**, 5229–5236.

Hu, Y., and C. Zhou, 2009: Decadal changes in the Hadley circulation. Vol. 10, *Advances in Geosciences,* J. H. Oh, Ed., World Scientific Publishing Company, Singapore, 250pp.

Hu, Y., K. Tung, and J. Liu, 2005: A closer comparison of early and late winter atmospheric trends in the Northern-Hemisphere. *J. Climate*, **18**, 2924–2936.

Hudson, R. D., M. F. Andrade, M. B. Follette, and A. D. Frolov, 2006: The total ozone field separated into meteorological regimes, Part II: Northern Hemisphere mid-latitude total ozone trends. *Atmos. Chem. Phys.*, **6**, 5183–5191.

Huffman, G. J., R. F. Adler, M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, 2001: Global precipitation at one-degree daily resolution from multi-satellite observations. *J. Hydrometeorol.*, **2**, 36–50.

Johanson, C. M., and Q. Fu, 2009: Hadley Cell Widening: Model Simulations versus Observations. *J. Climate*, **22**, 2713–2725.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kanamitsu, M., and Coauthors, 2002: NCEP-DOE AMIP-II reanalysis (R-2). *Bull. Amer. Meteor. Soc.*, **83**, 1631–1643.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate*, **11**, 1131–1149.

Liebmann, B., and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc.*, **77**, 1275–1277.

Lu, J., G. Vecchi, and T. Reichler, 2007: Expansion of the Hadley cell under global warming. *Geophys. Res. Lett.*, **34**, L06805, doi: 10.1029/2006GL028443.

Lu, J., G. Chen, and D. M. W. Frierson, 2008: Response of the zonal mean atmospheric circulation to El Niño versus global warming. *J. Climate*, **21**, 5835–5851.

Lu, J., C. Deser, and T. Reichler, 2009: The cause for the widening of the tropical belt since 1958. *Geophys. Res. Lett.,* **36**, L03803, doi: 10.1029/GL036076.

Mitas, C. M., and A. Clement, 2005: Has the Hadley cell been strengthening in recent decades? *Geophys. Res. Lett.*, **32**, L03809, doi: 10.1029/2004GL021765.

Mitas, C. M., and A. Clement, 2006: Recent behavior of the Hadley cell and tropical thermodynamics in climate models and reanalyses. *Geophys. Res. Lett.*, **33**, L01810, doi: 10.1029/2005GL024406.

Seidel, D. J., and W. J. Randel, 2007: Recent widening of the tropical belt: Evidence from tropopause observations. *J. Geophys. Res.*, **112**, D20113, doi: 10.1029/2007JD0 08861.

Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler, 2008: Widening of the tropical belt in a changing climate. *Nature Geoscience*, **1**, 21–24.

Son, S.-W., and Coauthors, 2008: The impact of stratospheric ozone recovery on the southern hemisphere westerly jet. *Science,* **320**, 1486–1489.

Son, S.-W., N. F. Tandon, L. M. Polvani, and D. W. Waugh, 2009: Ozone hole and Southern Hemisphere climate change. *Geophys. Res. Lett.,* **36**, L15705, doi: 10.1029/2009GL038671.

Uppala, S. M., and Coauthors, 2005: The ERA-40 reanalysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.

Wielicki, B. A., and Coauthors, 2002: Evidence for large decadal variability in the tropical mean radiative energy budget. *Science*, **295**, 841–844.

Wong, T., B. A. Wielicki, and R. B. Lee III, 2006: Reexamination of the observed decadal variability of the earth radiation budget using altitude-corrected ERBE/ERBS nonscanner WFOV data. *J. Climate*, **19**, 4028–4040.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448**, 461–465.