Intercomparison of the Intensities and Trends of Hadley, Walker and Monsoon Circulations in the Global Warming Projections

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Abstract

In this study, intensities and trends of Hadley, Walker, and monsoon circulations are compared for the IPCC 20th Century simulations and for 21st Century simulations, using the upper tropospheric velocity potential data. As a result, we showed significantly weaker biases in Walker and monsoon circulations for the JJA climate in the IPCC 20th Century simulations. The dispersion in the scatter diagram of the model biases is considerably large. The same analyses are applied for the IPCC 21st Century simulations to investigate the trends of these tropical circulations in response to the projected global warming. As a result, it is anticipated that Hadley, Walker, and monsoon circulations are weakened by 9.8% and 14%, respectively, by the late 21st Century, according to the ensemble mean of the IPCC model simulations. Considering the large model biases demonstrated for the IPCC 20th Century simulations, further studies are needed to quantify those trends.

1. Introduction

Intensities of large-scale tropical circulations, such as Hadley circulation, Walker circulation, and monsoon circulation, would change considerably in response to the global warming in the late 21st Century (see IPCC 2001). According to the projection by the atmosphere-ocean coupled general circulation model (CGCM) in the Meteorological Research Institute (MRI) in Japan (see Tokioka et al. 1995), the Hadley circulation is strengthened significantly in boreal summer for June to August (JJA). Conversely, the monsoon circulation is weakened for JJA as documented by Tanaka et al. (2004). A contradicting fact of increasing Indian summer monsoon rainfall after the global warming was explained by the increasing precipitable water in the monsoon area, despite the weakening monsoon circulation in the warmer than present climate (Kitoh et al. 1997).

The reliability of the future projection by the CGCMs may be justified, to some extent, by the comparison of the IPCC (Intergovernmental Panel on Climate Change) 20th Century model simulations with the observational records provided by NCEP (National Center for Environmental Prediction)/NCAR (National Center for Atmospheric Research) reanalysis or European Center for Medium-range Weather Forecasts reanalysis (ERA-40) data. Although the intensifying Hadley circulation in the 20th Century is confirmed by Quan et al. (2004) and Tanaka et al. (2004), the poor agreement between the IPCC 20th Century simulations and the major reanalyses is reported by Mitas and Clement (2005). For this reason, it is our major concern to compare the mean intensities and the trends of these tropical circulations for the numerous IPCC 20th Century and 21st Century simulations (see Meehl et al. 2005).

The purpose of this study is to conduct the intercomparison of the intensities of Hadley, Walker, and monsoon circulations for the IPCC 20th Century simulations. Intercomparisons are further extended to the IPCC 21st Century simulations for the global warming projections to find the anticipated trends.

2. Method and data

2.1 Different driving forces of tropical circulations

The quantitative assessment for variability of the circulation intensities has long been a major concern for Hadley, Walker, and monsoon circulations (e.g., Tanaka and Kimura 1996). These tropical circulations are driven by different dynamical causes. For example, the Hadley circulation in the general circulation context is driven by meridional differential diabatic heating. The essential structure may be axisymmetric because it occurs even in the hypothetical aqua-planet model. The Walker circulation, on the other hand, is driven by the different sea surface temperature (SST) along the equatorial tropics. Zonal asymmetry of the SST created by the continental interruption of major oceanic current may be the main cause of the Walker circulation. The monsoon circulation is driven essentially by the temperature contrast induced by the land-sea distributions. The seasonal reversal in the direction of the circulation between summer and winter may be the essential feature for the definition of the monsoon.

2.2 Analysis method

Velocity potential \( \psi \) at the 200 hPa level contains information concerning the overall intensity of the tropical circulations (see Fig. 1a). A separation of the velocity potential in terms of its characteristics in the space-time domain appears to be useful. Following Tanaka et al. (2004), we define the Hadley circulation first as an axisymmetric part of the circulation, i.e., \( \psi(x, y) \) (see Fig. 1b). Information on Walker and monsoon circulations is contained in the deviation from the zonal mean: i.e., \( \phi(t, x, y) \), where \( x, y \) and \( t \) represent longitude, latitude, and time, and \( \phi \) and \( \phi^* \) stand for the zonal mean and the deviation from it, respectively. Second, we define the monsoon circulation as a part of the seasonal change of the deviation field. For this
reason, the annual mean is subtracted from the deviation field to define the monsoon circulation: i.e., $\chi' (t, x, y)$ (see Fig. 1d). Finally, we define the Walker circulation as the remainder which is the annual mean of the zonal deviation field: i.e., $\chi^\prime\prime (x, y)$ (see Fig. 1c), where $\langle \rangle$ and $\langle \prime \rangle$ stand for the annual mean and the deviation from it, respectively.

With these simple definitions of the tropical circulations, the velocity potential is divided into the following linear combinations of three independent components:

$$\chi (t, x, y) = [-\chi] (t, y) + \chi^\prime (x, y) + \chi^\prime\prime (t, x, y). \quad (1)$$

In the right hand side, the first, second, and third terms are thus defined as components of the Hadley, Walker, and monsoon circulations, respectively. In analyzing interannual variability, 12-month running means are used in place of the $\langle \rangle$, and $\langle \prime \rangle$ is the deviation from the running mean.

The intensities of the Hadley, Walker, and monsoon circulations are defined by the peak values of the separated velocity potential in Figs. 1b, 1c, and 1d, respectively. The mathematical circulation, i.e., a line integral of tangential wind speed along a closed circle, may be represented by the peak values of the velocity potential as described in Tanaka et al. (2004). According to the analyses of the 20C3M for the MRI-CGCM2-3-2A (see Fig. 1), the mean intensities of Hadley, Walker, and monsoon circulations in JJA are respectively 35: 120: 80 units for the NCEP/NCAR reanalysis (see Fig. 2).

Although the tropical circulations are separated in those three components, they are highly interacting nonlinearly. The definition may be too simple to describe the complex tropical circulations. However, we expect that the present definition retrieves the essence of the tropical circulations as demonstrated in Fig. 1.

2.3 Data

The data used in this study are the sets of 20th (20C3M) and 21st (SRES A1B) Century climate model simulations performed for the IPCC 4th Assessment Report (AR4), provided by the U.S. Department of Energy Program for Climate Model Diagnosis and Intercomparison (PCMDI). The SRES A1B projects 720 ppm CO$_2$ concentration stabilized by the year 2100 under the very rapid economic growth with increasing globalization.

Among the numerous data collections, 15 climate model simulations are selected in this study (see Table 1): Météo-France (CNRM-CM3), CSIRO, Australia (CSIRO-MK3-0), GFDL, USA (GFDL-CM2-1), GISS, USA (GISS-MOM; GISS-MODEL-E-H; GISS-Model-E-R), INM, Russia (INMCM3-0), IPSL, France (IPSL-CM4), CCSR/NIES/FRCGC (noted as CNF), Japan (MIROC3-2-HIRES; MIROC3-2-MEDRES), MPI, Germany (MPI-ECHAM5), MRI, Japan (MRI-CGCM2-3-2A), NCAR, USA (NCAR-CCSM3-0; NCAR-PCM1), and UKMO, UK (UKMO-HADCM3). Refer to Meehl et al. (2005) for the detail of the data descriptions.

3. The intensities for the IPCC 20th Century simulations

Figure 2 plots the distributions of Hadley, Walker, and monsoon circulation intensities in JJA for the IPCC 20th Century simulations (20C3M) during 1981 to 2000 to assess the model performance for the present climate. For reference, the results from the NCEP/NCAR reanalysis (Kalnay et al. 1996) for 1966-2000 are marked by white circles (after Tanaka et al. 2004). It should be noted that the NCEP/NCAR reanalysis may contain considerable amount of biases as discussed in Mitas and Clement (2005). The intensities of Hadley circulation (abscissa of Fig. 2a) are scattered in the range of 20 to 50 ($\times 10^5$ m$^2$ s$^{-1}$) while that of the NCEP/NCAR reanalysis is 40 units. The multi-model ensemble mean of the Hadley circulations (35 units) is slightly weaker than the NCEP/NCAR reanalysis. For example, INMCM3-0 is only a half of MIROC3-2-HIRES. The intensities of Walker circulation (abscissa of Fig. 2b) are scattered in the range of 40 to 130 while that of the NCEP/NCAR
reanalysis is 120 units. It is found that the ensemble mean of the Walker circulations (97 units) is considerably weaker than that of observations. Quantitatively, GISS-MODEL-E-H is only one third of UKMO-HADCM3 in its intensity. The intensities of the monsoon circulation (abscissa of Fig. 2c) are scattered in the range of 50 to 80 while that of the NCEP/NCAR reanalysis is 80 units. It is interesting to note that the ensemble mean of the monsoon circulations (66 units) is significantly weak compared with the reanalysis.

The linear correlations among Hadley, Walker, and monsoon circulation intensities are examined in Fig. 2 by the scatter diagrams. It seems that there is no marked correlation among those tropical circulation intensities, although a minor correlation is seen between the Walker and monsoon circulations.

4. The trends for the IPCC 21st Century simulations

Finally, the same analyses are applied for the IPCC 21st Century simulations (SRES A1B) to investigate the trend of the tropical circulation intensities after the global warming. The projected time series of Hadley, Walker, and monsoon circulation intensities in JJA are
provided in the Supplement 1.

Figure 3 illustrates the intensity differences between the future (21st Century: 2081–2100) and present (20th Century: 1981–2000) IPCC simulations in JJA. The differences (i.e., trends) of the Hadley circulation intensities (abscissa of Fig. 3a) are scattered in the range of −20 to +5 with the ensemble mean of −3 units. It is projected that Hadley circulations become weaker during the 21st Century by approximately 9% for the ensemble mean. The result for MIROC3-2-HIRES indicates a drastic decrease by 54% as seen from Fig. 3 and the time series in the Supplement 1. The trends of the Walker circulation intensities (abscissa of Fig. 3b) are scattered in the range of −30 to +20 with the ensemble mean of −8 units. Except for GFDL-CM2-1, all other simulations indicate weakening trends by approximately 8% in the ensemble mean and up to 30% for MPI-ECHAM5. The trends of the monsoon circulation intensities (abscissa of Fig. 3c) are scattered in the range of −25 to +5 with the ensemble mean of −9 units. It is projected that monsoon circulations become weaker during the 21st Century for most of the IPCC simulations by approximately 14% in the ensemble mean and up to 36% for MIROC3-2-HIRES.

The linear correlations among Hadley, Walker, and monsoon circulation intensities are examined in Fig. 3 by the scatter diagrams. It seems that there is no significant correlation among those tropical circulation intensities, although a minor correlation is seen between the Walker and monsoon circulations. The result suggests that MIROC3-2-HIRES is subject to be considered as an outlier with strong climate drift which disagrees with others. However, of course, climate projections should not be based on the CGCM consensus.

5. Concluding summary

In this study, intensities and trends of Hadley, Walker, and monsoon circulations are compared for the IPCC 20th Century simulations (20C3M) and for 21st Century simulations (SRES A1B), using the upper tropical (200 hPa) velocity potential data. Following the argument by Tanaka et al. (2004), the tropical circulations are separated considering their different driving forces, and the intensities are measured by the peak values of the separated velocity potential.

As a result of the analysis for JJA, we showed that the mean intensities of the Hadley, Walker, monsoon circulations for the IPCC 20th Century simulations are 35: 97: 66 (×10^7 m^2 s^-1) in the ensemble means, which are compared with 40: 120: 80 for the NCEP/NCAR reanalysis. The significantly weaker biases in the divergent wind may be attributable to the positive bias of tropical static stability in the upper troposphere as speculated by Knutson and Manabe (1995) and Mitas and Clement (2005).

The same analyses are extended to the IPCC 21st Century simulations to investigate the trends in response to a global warming scenario. As a result, it is anticipated that the Hadley circulation becomes weaker by 9%, Walker circulation by 8%, and monsoon circulation by 14% by the late 21st Century as an ensemble mean of the IPCC model simulations.

In our former study (Tanaka et al. 2004), a drastic intensifying trend of the Hadley circulation and significant weakening trend of monsoon circulation were reported for the MRI-CGCM1 climate prediction. The future projection is totally replaced by the new version of the MRI-CGCM2 for the IPCC 21st Century simulations, suggesting the high degree of model-dependent sensitivity of those tropical circulations. Although the intensity trends are evaluated as the ensemble mean of the IPCC simulations, those trends are statistically insignificant according to Santer et al. (1999), considering the range of the uncertainty due to the large model biases demonstrated for the IPCC 20th Century simulations. The results in this study are consistent with the assessment by Mitas and Clement (2005), suggesting a poor capability of reproducing and predicting the tropical circulations by the current CGCMs.

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Comments and supplements


References


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