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Advances in Climate Change Research 7 (2016) 35−45

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Climatology and interannual variability of the annual mean Hadley circulation in CMIP5 models

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Received 16 March 2016; accepted 28 April 2016
Available online 10 May 2016

Abstract

Using 26 climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), climatology and the interannual variability of the annual mean Hadley circulation are evaluated. The results show that most of 26 models perform well in simulating the spatial structure of the climatology of the annual mean Hadley circulation, but the results derived from these models are generally weaker than that derived from the reanalysis dataset. Eighteen models can properly simulate well the asymmetric mode and symmetric mode of the annual mean Hadley circulation variability. Two models can only simulate asymmetric mode or symmetric mode and the other two models simulate reversed sequences of asymmetric mode and symmetric mode.

The possible reason why some models cannot properly simulate the asymmetric mode and symmetric mode is that these models do not properly simulate the structure of zonal mean sea surface temperature (SST). Especially, not properly simulating variances of symmetric and asymmetric components of the SSTA will lead to reversed sequence of symmetric mode and asymmetric mode. And not properly simulated either symmetric or asymmetric component of the SSTA will lead to inability in simulating symmetric mode or asymmetric mode. On the other hand, some models properly simulate the asymmetric mode and symmetric mode, but do not properly simulate the responses to SST change. These models can not reflect the air sea coupling processes in associated with the Hadley circulation, therefore they should be taken more care when classify the models into groups.

Keywords: Hadley circulation; CMIP5 models; Symmetry; Meridional SST gradient

1. Introduction

As one of the most important large-scale circulations in the tropics, Hadley circulation (HC) plays an important role in modulating the climate system, such as the hydrological process (Schneider et al., 2010), the subtropical droughts (Fu et al., 2006), the tropical cyclone (Zhang and Wang, 2013, 2015) and the extratropical climate (Hou, 1998). Due to the importance of HC research, more and more attentions have been paid to the changes of HC in recent years.

Although there are many studies discussing the changes of HC, no consensus has been reached about the changes of HC intensity. Using the observational datasets, some studies showed that the intensity of the annual mean HC increased in the 1990s (Chen et al., 2002; Wielicki et al., 2002). However, some subsequent studies reported that the intensity of HC is seasonally dependent. In the boreal winter (December, January

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Peer review under responsibility of National Climate Center (China Meteorological Administration).

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.accre.2016.04.005

and February, DJF), HC has strengthened since the 1950s (Quan et al., 2004; Ma and Li, 2007, 2008; Feng et al., 2013; Mitas and Clement, 2005); Feng et al. (2013) further pointed out that in boreal spring, the HC also intensified; but some other studies revealed that the strength of the HC in boreal summer shows no significant increasing trend (Tanaka et al., 2004; Feng et al., 2011).

In addition to the intensity, the HC width also attracts lots of attentions. It is reported that the HC has a poleward expansion trend since 1979 (Fu et al., 2006; Frierson et al., 2007; Lu et al., 2007; Seidel et al., 2008; Hu and Fu, 2007; Hu et al., 2011; Johanson and Fu, 2009). The widening of the HC results in a poleward extension of the subtropical dry zones (Polvani et al., 2011).

Given the fact that HC has important climate impacts, its spatial structure is also worth investigating. Dima and Wallace (2003) found that the annual march of HC is consisted of two components: the asymmetric and symmetric parts. Subsequently, Ma and Li (2008) found that the principal modes of the year-to-year variability of DJF HC show asymmetric mode (AM) for EOF1 and symmetric mode (SM) for EOF2. Similar results were also obtained in boreal summer and spring (Feng et al., 2011, 2013; Li et al., 2013). Feng and Li (2013) pointed out that the classical El Niño events have different impact on HC structure from that of the El Niño Modoki events. The former can lead to symmetric HC anomaly, while the latter will lead to asymmetric HC anomaly. The asymmetric HC anomaly is documented to have impacts on subtropical precipitation (Feng et al., 2013; Li et al., 2015) and tropical cyclone (Zhang and Wang, 2013).

The above mentioned studies indicate that the HC variability is complex and has important climate impacts. Understanding the HC variability and its future change are quite necessary. However, the trends of the HC are inconsistent among different datasets because of the atmospheric thermal structure bias (Stachnik and Schumacher, 2011; Nguyen et al., 2013; Mitas and Clement, 2006). To better understand how HC changes, the high-performance numerical models are needed. The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides useful benchmark for evaluating the state-of-art coupled models' performance in simulating the climate system. Previous studies demonstrated that the current climate models underestimated the poleward expansion of the HC (Hu et al., 2013; Quan et al., 2014). Feng et al. (2015) even pointed out that no models can capture the long-term trend in the AM of annual mean HC due to the failure in simulating the interhemispheric sea surface temperature (SST) difference among the 10 CMIP5 models they selected. Hence, it is important to analyze the climatology and interannual variability of the annual mean HC simulation by using more CMIP5 models.

Table 1
A brief introduction of the CMIP5 models used in this study.

Model	Institution and country	Layers	Atmospheric resolution
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	26	128 × 64
CESM1-CAM5	Community Earth System Model contributors	17	192 × 288
HadCM3	Met Office Hadley Centre	17	72 × 96
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	17	64 × 128
CCSM4	National Center for Atmospheric Research	26	288 × 192
CanESM2	Canadian Centre for Climate Modelling and Analysis	35	128 × 64
CESM1-WACCM	Community Earth System Model contributors	23	96 × 144
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	31	256 × 128
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)	18	192 × 96
EC-EARTH	EC-EARTH consortium	16	160 × 320
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	26	128 × 60
FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	26	128 × 108
FIO-ESM	First Institute of Oceanography, State Oceanic Administration (SOA), China	17	64 × 128
GFDL-CM3	NOAA/Geophysical Fluid Dynamics Laboratory	48	144 × 90
GFDL-ESM2G	NOAA/Geophysical Fluid Dynamics Laboratory	17	90 × 144
GFDL-ESM2M	NOAA/Geophysical Fluid Dynamics Laboratory	17	90 × 144
GISS-E2-H	NASA Goddard Institute for Space Studies	17	89 × 144
GISS-E2-R	NASA Goddard Institute for Space Studies	17	90 × 144
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration	17	144 × 192
inmcm4	Institute of Numerical Mathematics	17	120 × 180
IPSL-CM5A-LR	L'Institute Pierre-Simon Laplace	17	96 × 96
MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	17	128 × 256
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, and Ocean Research Institute (University of Tokyo), and National Atmosphere Institute for Environmental Studies	35	64 × 128
MPI-ESM-LR	Max Planck Institute for Meteorology	25	96 × 192
MRI-CGCM3	Meteorological Research Institute	23	160 × 320
NorESM1-M	Norwegian Climate Centre	17	96 × 144