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Twentieth-century Pacific Decadal Oscillation simulated by CMIP5 coupled models

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ABSTRACT

The authors examine the spatial and temporal characteristics of the simulated Pacific Decadal Oscillation (PDO) in 109 historical (i.e. all forcings) simulations derived from 25 coupled models within CMIP5. Compared with observations, most simulations successfully simulate the observed PDO pattern and its teleconnections to the SSTs in the tropical and southern Pacific. BNU-ESM, CanESM2, CCSM4, CESM1-FASTCHEM, FGOALS-g2, GFDL CM3, MIROC5, and NorESM1-M show better performance. Compared with the temporal phases of the observed PDO in the twentieth century, only five simulations — from CNRM-CM5, CSIRO Mk3.6.0, HadCM3, and IPSL-CM5A-LR — simulate an evolution of the PDO similar to that derived from observation, which suggests that current coupled models can barely reproduce the observed phase shifting of the PDO. To capture characteristics of the observed PDO in the twentieth century, a requirement is that all the relevant external forcings are included in the models. How to add realistic oceanic initial states into the model may be another key point.

摘要

太平洋年代际振荡(PDO)是影响亚洲—太平洋气候,乃至全球气候变化非常重要的海洋模态 之一。目前为止,有关PDO形成的动力根源及机制仍不清楚。本文聚焦20世纪PDO的空间模态 和时间序列演变,系统分析了CMIP5框架下25个耦合模式开展的109个历史时期模拟试验的结 果。结果显示,大多数耦合模式可以成功模拟出20世纪PDO"马蹄形"海表温度距平,其中BNU-ESM,CanESM2,CCSM4,CESM1-FASTCHEM,GFDLCM3,MIROC5,NorESM1-M等模式和中国 科学院大气物理研究所的FGOALS-g2模拟的PDO太平洋海表温度遥相关型空间分布与观测相似 度较高;耦合模式模拟的PDO时间序列与观测相差较大,表明现有的耦合模式几乎不能模拟出 20世纪PDO的位相演变特征。

1. Introduction

The Pacific Decadal Oscillation (PDO) is one of the most important modes of decadal climate variability (Mantua et al. 1997; Mantua and Hare 2002), whose index is defined as the leading principal component of SST anomalies in the Pacific basin, poleward of 20°N. Based on the last 100 years of observations, the spatial pattern of the PDO shows a characteristic 'horseshoe' shape in the North Pacific. During a positive PDO phase, anomalously cool SSTs are observed in the Kuroshio–Oyashio extension and central North Pacific, surrounded by anomalously warm SSTs along the west coast of the Americas that extend towards the tropics (Figure 1, observation). The spatial pattern is reversed during a negative PDO phase.

Previous studies indicate that the PDO has significant influences on regional, or even global climate. Fox example,

its regime shifts have been associated with long-term fluctuations of the East Asian summer monsoon (e.g. Yu et al. 2015; Dong and Xue 2016), dry/wet conditions in North China (e.g. Wang et al. 2013; Qian and Zhou 2014; Zhu et al. 2015), Australian rainfall (Arblaster, Meehl, and Moore 2002; Cai and van Rensch 2012), and climate changes over the North Pacific and its coasts (Mantua and Hare 2002; Deser, Phillips, and Hurrell 2004). Additionally, the recent global-warming hiatus has also been partly attributed to the negative PDO-like SSTs in the early years of the twenty-first century (Kosaka and Xie 2013).

Despite its importance, the root cause of the PDO is still unclear. Local air-sea interactions in the North Pacific are suggested as a crucial process for the PDO. An anomalous Aleutian low and anomalous advection in the Kuroshio-Oyashio extension and the subtropical-gyre have also

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Figure 1. Observed and simulated regression distributions of SST on the PDO index (units: °C). Notes: Results for only the first member (i.e. r1i1p1) of all 25 coupled models are shown in this figure. The explained variance for each model is shown in the upper right-hand corner (units: %).

been invoked to explain the PDO (Latif and Barnett 1994; Schneider and Cornuelle 2005; Sun and Wang 2006). However, Deser, Phillips, and Hurrell (2004) suggested that the tropics should play a key role in North Pacific interdecadal climate variability. At the same time, the remote influence from the Atlantic Multidecadal Oscillation cannot be excluded (Zhang and Delworth 2007). Therefore, this issue is so complicated that the mechanisms responsible for the PDO are open disputed.

In the twentieth century, the PDO experienced four regime shifts, in roughly 1925, 1946, 1977, and 1999 (http://research.jisao.washington.edu/pdo/). Although, as an internal variability, the PDO and its regime shifts are most likely influenced by external forcings (e.g. solar irradiance, volcanoes, anthropogenic greenhouse gases, and aerosols) (Wang et al. 2012; Dong, Zhou, and Chen 2014). Therefore, all relevant external forcings are needed for a model to obtain the correct timing of the simulated PDO in the twentieth century. There is a large amount of historical simulations within CMIP5. Both the natural and anthropogenic forcings covering the period 1850–2005 have been added into the models in these simulations. A more recent study indicated that most coupled models in CMIP5 have good capacity to simulate the climate mean state of the Asian-Pacific climate (Zhou 2016). Nevertheless, the skill of these coupled models in modelling the PDO remains unclear. In the present study, therefore, we use CMIP5 historical simulations to examine the performance of multiple models for the simulation of the spatial pattern and evolution of the PDO during the entire twentieth century.

The rest of this paper is organized as follows: Section 2 describes the models, experimental design, and the method employed. In Section 3, the simulated PDO in the CMIP5 coupled models is compared with observations. Finally, conclusions and a discussion are given in Section 4.

2. Model experiments, data, and method

A total of 109 historical simulations from 25 coupled models in CMIP5 (Taylor, Stouffer, and Meehl 2012) are analyzed in this study. The coupled models in the historical simulations (also called all-forcing simulations) are forced by both natural (total solar irradiance and volcanoes) and anthropogenic (well-mixed greenhouse gases and anthropogenic aerosols) forcings, which cover the period from 1850 to 2005. The details of the CMIP5 coupled models, including the model acronyms and affiliations, are listed in Table 1. The observed SST used in this study is from the Hadley Center's monthly SST data-set (Rayner et al. 2003).

In this study, we calculated the PDO index as the leading principal component of SST anomalies in the North

Table 1. Details of the 25 CMIP5 coupled models in this study.

No.	Model	Institute/Country	Member
1	BCC_CSM1.1	BCC/China	3
2	BNU-ESM	BNU/China	1
3	CanESM2	CCCma/Canada	5
4	CCSM4	NCAR/USA	6
5	CESM1-CAM5	NCAR/USA	3
6	CESM1-FASTCHEM	NCAR/USA	3
7	CNRM-CM5	CNRM-CERFACS/France	10
8	CSIRO Mk3.6.0	CSIRO-QCCCE/Australia	10
9	FGOALS-g2	IAP-THU/China	5
10	GFDL CM3	NOAA-GFDL/USA	5
11	GFDL-ESM2M	NOAA-GFDL/USA	1
12	GISS-E2-H	NASA-GISS/USA	6
13	GISS-E2-R	NASA-GISS/USA	6
14	HadCM3	MOHC/UK	10
15	HadGEM2-ES	MOHC/UK	4
16	IPSL-CM5A-LR	IPSL/France	6
17	IPSL-CM5A-MR	IPSL/France	3
18	MIROC5	MIROC/Japan	4
19	MIROC-ESM	MIROC/Japan	3
20	MIROC-ESM-CHEM	MIROC/Japan	1
21	MPI-ESM-LR	MPI-M/Germany	3
22	MPI-ESM-MR	MPI-M/Germany	3
23	MPI-ESM-P	MPI-M/Germany	2
24	MRI-CGCM3	MRI/Japan	3
25	NorESM1-M	NCC/Norway	3

Pacific (poleward of 20°N). Before the EOF analysis, the global warming signal is removed from the data by subtracting the mean global SST anomaly. For the entire twentieth century, we focus on the spatiotemporal characteristics of the PDO in the Northern Hemisphere winter (i.e. November–March), because the PDO behavior is substantially intensified in winter (Mantua et al. 1997; Deser and Phillips 2006). We use the regular-grid surface temperature (i.e. the CMIP5 output variable 'ts') over the ocean instead of the irregular-grid SST fields in the analysis of modeled data. In addition, we set the surface temperature in regions covered by sea ice to -1.8 °C according to the observed SST data-set (Rayner et al. 2003).

To evaluate the effectiveness of the models for the simulation of the PDO, the spatial correlation coefficient (SCC) of the PDO teleconnection patterns and the correlation coefficient of the PDO indices between the observations and CMIP5 coupled models are computed in this study. The multi-model ensemble simulation is calculated as the arithmetic mean of the ensemble simulation for the multi-member 22 coupled models with multi-member simulations (i.e. greater than one member). The Pearson's linear correlation coefficient is used to describe the significance of the correlation coefficients. To highlight the decadal signals, the 9-yr running mean is used on all of the PDO indices before calculating the correlation coefficients of the time series. The formula of Quenouille (1952) is used to estimate the effective degrees of freedom (N_{o}) of the 9-yr running mean indices:

$$N_{\rm e} = \frac{N}{1 + 2\sum_{i=1}^{10} a_i b_i},$$

where *N* is the number of data points, and a_i and b_i are the *i*th order autocorrelations for time series *a* and *b*, respectively.

3. Results

As shown in the regression map (Figure 1), the observed SSTs are anomalously cool in the western-central region of the North Pacific during the positive PDO phase, and are surrounded by anomalously warm SSTs along the west coast of the Americas. At the same time, El Niño–like SST anomalies are evident in the central-eastern tropical Pacific, but negative SST anomalies are observed in the subtropical South Pacific. The explained variance for the PDO pattern is 33.2% in the observations. Compared with the observations, most coupled models in CMIP5 reproduce the PDO pattern well, particularly in the North Pacific, which is also the case for the CMIP5 last millennium simulations (Fleming and Anchukaitis 2016). BNU-ESM,

CanESM2, CCSM4, CESM1-CAM5, CSIRO Mk3.6.0, GFDL CM3, GFDL-ESM2M, HadCM3, HadGEM2-ES, MIROC5, and NorESM1-M reproduce the observed teleconnections of the PDO to SSTs in the tropical and Southern Pacific well. These simulated teleconnections in other models are relatively weak, particularly for the r1i1p1 simulations of BCC CSM1.1, CNRM-CM5, GISS-E2-H, and MRI-CGCM3. Based on the statistical results, BNU-ESM, CanESM2, CCSM4, CESM1-FASTCHEM, FGOALS-g2, GFDL CM3, MIROC5, and NorESM1-M better depict the PDO pattern (Table 2). The SCCs of the PDO regression maps between the observations and these models are greater than 0.8. Additionally, the CanESM2, CCSM4, CESM1-FASTCHEM, FGOALS-g2, MIROC5, and NorESM1-M simulate a higher explained variance for the PDO pattern (~30%), which is comparable to the observations. In the r1i1p1 simulations of GISS-E2-R, MPI-ESM-LR, and MRI CGCM3, the explained variance for the PDO pattern is small, at less than 20%.

The ensemble results for the 22 coupled models (i.e. multi-model ensemble) are shown in Figure 2. MIROC5 reproduces the PDO pattern most similar to the observations. Its SCC is 0.88, which is greater than most single-model ensemble simulations. The

Model	r1i1p1/r6i1p1	r2i1p1/r7i1p1	r3i1p1/r8i1p1	r4i1p1/r9i1p1	r5i1p1/r10i1p1	Mean value	Ensemble simulation
BCC_CSM1.1	0.42	0.67	0.37			0.49	0.44
BNU-ESM	0.84						
CanESM2	0.83	0.81	0.83	0.87	0.82	0.83	0.84
CCSM4	0.82	0.86	0.86	0.76	0.91	0.86	0.89
	0.92						
CESM1-CAM5	0.71	0.80	0.76			0.76	0.88
CESM1- FASTCHEM	0.81	0.84	0.85			0.83	0.86
CNRM-CM5	0.65	0.63	0.53	0.39	0.49	0.56	0.10
	0.63	0.57	0.72	0.69	0.30		
CSIRO Mk3.6.0	0.64	0.71	0.71	0.58	0.59	0.66	0.66
	0.60	0.64	0.76	0.70	0.66		
FGOALS-g2	0.86	0.83	0.86	0.81	0.80	0.83	0.83
GFDL CM3	0.89	0.84	0.85	0.87	0.86	0.86	0.87
GFDL-ESM2M	0.69						
GISS-E2-H	0.28	0.77	0.72	0.67	0.59	0.61	0.70
	0.61						
GISS-E2-R	0.82	0.79	0.68	0.69	0.72	0.76	0.82
	0.85						
HadCM3	0.59	0.54	0.51	0.56	0.63	0.58	0.61
	0.73	0.39	0.70	0.65	0.53		
HadGEM2-ES	0.83	0.84	0.82	0.76		0.81	0.76
IPSL-CM5A-LR	0.79	0.73	0.75	0.71	0.78	0.75	0.70
	0.71						
IPSL-CM5A-MR	0.78	0.76	0.83			0.79	0.79
MIROC5	0.88	0.88	0.85	0.87		0.87	0.88
MIROC-ESM	0.68	0.69	0.71			0.69	0.69
MIROC-ESM- CHEM	0.70						
MPI-ESM-LR	0.57	0.55	0.70			0.61	0.68
MPI-ESM-MR	0.75	0.68	0.66			0.70	0.78
MPI-ESM-P	0.51	0.67				0.59	0.10
MRI-CGCM3	0.71	0.74	0.51			0.65	0.64
NorESM1-M	0.86	0.81	0.83			0.83	0.83

Table 2. Spatial correlation coefficients (SCCs) of the PDO regression maps between the observation and simulations.

Notes: r1i1p1–r10i1p1 stand for the member names of the CMIP5 all-forcing simulations. The mean value is the average of all members' SCCs. The ensemble simulation is the SCC between the observation and ensemble simulation for each model.



Figure 2. Observed and simulated regression distributions of SST on the PDO index (units: °C). Notes: The model results are derived from ensemble simulations for each model. The last figure is for the multi-model ensemble simulation.

SCC of the CCSM4 ensemble simulation is 0.89, and is the highest SCC. However, the intensity of its PDO pattern is weaker than in the observations, as is the case for the other single-model ensemble simulations. This suggests that the internal variability of the PDO is weakened to some extent by the ensemble average, particularly for simulations by the larger members (e.g. CNRM-CM5 and CSIRO Mk3.6.0; Figure 2). In the multi-model ensemble simulation, the simulated PDO pattern explains 38.1% of the total variance of the SST anomalies. The SCC between the PDO pattern and the observations is as high as 0.81 (Figure 3). However, the teleconnections to the SST anomalies are very weak, as also seen in Figure 3.

Many climate shifts are closely tied to the phase transition of the PDO (e.g. Hartmann and Wendler 2005; Zhu et al. 2011; Lyon, Barnston, and DeWitt 2014). Therefore, more attention has been paid to the evolution of the PDO and its phase shifts. In the twentieth century, the observed PDO enters a positive phase in the early 1920s, and then a negative phase in the early 1940s (Figure 4). Finally, it returns to a positive phase again in the late 1970s. The simulated PDO evolutions in the twentieth century are very different from one another. Different external forcings



Figure 3. Simulated regression distribution of SST on the PDO index (units: °C) in the multi-model ensemble simulation.

(e.g. volcanic forcing and anthropogenic aerosols) used in these models can contribute to the differences in simulated PDO evolutions. Even for individual models and forced by the same external forcings, the simulated PDO evolutions are also different among members. This means that the initial states probably play an important role in shaping subsequent PDO evolution. Compared to the observations, therefore, most simulations do not reproduce the observed temporal phases of the PDO (Table 3). However, eight simulations produce a similar PDO evolution as observed (Figure 4). These are the r5i1p1 simulation of CanESM2, the r3i1p1 and r8i1p1 simulations of CNRM-CM5, the r6i1p1 simulation of CSIRO Mk3.6.0, the r3i1p1 simulation of GISS-E2-R, the r8i1p1 simulation of HadCM3, the r4i1p1 simulation of IPSL-CM5A-LR, and the r1i1p1 simulation of MPI-ESM-LR. The simulated PDO time series in five simulations are significantly associated with the observed PDO index. Their correlation coefficients are greater than 0.36 (p < 0.05; Table 3), which suggests that some of the coupled models, forced by all relevant external forcings, could by chance reproduce the observed PDO evolution to some extent. Additionally, the r6i1p1 simulation of CSIRO Mk3.6.0 reproduces the PDO evolution in the second half of the twentieth century well (Figure 4).

No ensemble simulations reproduce the observed PDO evolution (Table 3). In CanESM2, GFDL CM3, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-MR, and MIROC-ESM ensemble simulations, and the multi-model ensemble, the



Figure 4. Observed and simulated PDO indices.

Notes: Shading stands for the observations. In the observation figure, the black line stands for the simulated PDO index in the multi-model ensemble simulation of the 22 coupled models (excluding BNU-ESM, GFDL-ESM2M, and MIROC-ESM-CHEM).

Model	r1i1p1/r6i1p1	r2i1p1/r7i1p1	r3i1p1/r8i1p1	r4i1p1/r9i1p1	r5i1p1/r10i1p1	Ensemble simulation
BCC_CSM1.1	0.12	-0.03	-0.29			-0.06
BNU-ESM	0.09					
CanESM2	-0.12	0.00	-0.08	0.03	0.32*	0.04
CCSM4	-0.10	0.09	-0.07	0.23	-0.03	0.00
	-0.11					
CESM1-CAM5	0.03	0.03	-0.42**			-0.17
CESM1-FASTCHEM	-0.06	0.07	0.11			0.13
CNRM-CM5	-0.20	-0.03	0.45**	0.02	0.29	-0.32*
	-0.03	-0.11	0.43**	-0.17	-0.23	
CSIRO Mk3.6.0	0.15	0.21	-0.29*	-0.07	0.21	-0.05
	0.42**	-0.16	0.07	-0.06	-0.02	
FGOALS-g2	-0.31	-0.08	0.12	-0.01	-0.23	-0.20
GFDL CM3	0.27	0.08	0.07	0.00	-0.26	0.02
GFDL-ESM2M	-0.03					
GISS-E2-H	0.03	0.06	-0.18	-0.21	-0.09	0.01
	-0.05					
GISS-E2-R	0.15	-0.38**	0.33*	0.10	-0.09	-0.04
	-0.21					
HadCM3	0.02	-0.16	-0.17	-0.03	0.08	-0.01
	-0.27	0.17	0.36**	-0.08	-0.07	
HadGEM2-ES	-0.05	0.09	-0.04	-0.06		-0.04
IPSL-CM5A-LR	-0.04	-0.01	-0.33*	0.39**	0.06	0.01
	-0.12					
IPSL-CM5A-MR	-0.18	-0.10	-0.20			-0.20
MIROC5	-0.26	0.17	-0.18	-0.22		-0.14
MIROC-ESM	0.16	0.15	0.05			0.13
MIROC-ESM-CHEM	0.22					
MPI-ESM-LR	0.29*	-0.16	0.12			0.04
MPI-ESM-MR	-0.16	-0.16	-0.01			-0.22
MPI-ESM-P	-0.09	-0.12				-0.07
MRI-CGCM3	-0.00	0.05	0.14			0.16
NorESM1-M	0.16	-0.08	0.07			0.04

Table 3. Correlation coefficients between the observed and simulated PDO indices, and between the observation and ensemble simulation for each model.

Notes: Single and double asterisks stand for the p values being smaller than 0.1 and 0.05, respectively.

*Bold values stand for the simulations which reproduce the observed PDO evolution.

simulated PDO indices show a significant long-term tendency to the positive phase in the twentieth century. One reason for large discrepancies between the observed and simulated PDO indices may be that the internal variability of the PDO has been averaged out in the ensemble simulations, as noted by Dong, Zhou, and Chen (2014). Particularly for the multi-model ensemble, the positive trend of simulated PDO index probably reflects the response of the PDO to increasing levels of the greenhouse gases in the twentieth century (Dong, Zhou, and Chen 2014), which are the same for all the coupled models in this study.

4. Summary and discussion

We examine the spatial and temporal characteristics of the PDO in the 109 historical simulations from 25 coupled models in CMIP5. Most of the simulations successfully reproduce the 'horseshoe' shape SST anomalies in the North Pacific and observed PDO teleconnections to SSTs in the tropical and South Pacific. Additionally, BNU-ESM, CanESM2, CCSM4, CESM1-FASTCHEM, FGOALS-g2, GFDL CM3, MIROC5, and NorESM1-M better simulate the PDOassociated SST pattern in the Pacific. The SCCs between the observed and simulated PDO regression maps are greater than 0.8.

Compared with the observed PDO evolution in the twentieth century, only five simulations of a total of 109 historical members simulate similar temporal phases of the PDO. The correlation coefficients between the simulated and observed PDO indices are greater than 0.36 for the r3i1p1 and r8i1p1 simulations of CNRM-CM5, the r6i1p1 simulation of CSIRO Mk3.6.0, the r8i1p1 simulation of HadCM3, and the r4i1p1 simulation of IPSL-CM5A-LR. Their similarity is significant at the 0.05 significance level. It suggests that coupled models, forced by all the relevant external forcings, can by chance reproduce the observed PDO evolution. In other words, the current coupled models barely simulate the temporal evolution of the observed PDO in the twentieth century. Perhaps realistic initial states of the oceanic field are necessary for the models to capture the temporal characteristics of the PDO.

We also analyze the simulated PDO in the ensemble simulation for each coupled model and in the multi-model ensemble. After the ensemble average, different internal variabilities from multi-member simulations interfere with one another. Particularly for the multi-model ensemble, some external forcings (e.g. volcanic forcing and anthropogenic aerosol forcing) used in these coupled models are different. Therefore, it is not appropriate to investigate the impacts of the internal modes (e.g. the PDO and the Atlantic Multidecadal Oscillation) on the regional and global climate using ensemble simulations, because the internal variabilities from different members are not consistent and interfere with one another.

Disclosure statement

No potential conflict of interest was reported by the authors.

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