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A Robustness Analysis of CMIP5 Models over the East Asia-Western North Pacific Domain

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ABSTRACT

The Coupled Model Intercomparison Project (CMIP) is an international community-based infrastructure that supports climate model intercomparison, climate variability, climate prediction, and climate projection. Improving the performance of climate models over East Asia and the western North Pacific has been a challenge for the climate-modeling community. In this paper, we provide a synthesis robustness analysis of the climate models participating in CMIP-Phase 5 (CMIP5). The strengths and weaknesses of the CMIP5 models are assessed from the perspective of climate mean state, interannual variability, past climate change during the mid-Pliocene (MP) and the last millennium, and climate projection. The added values of regional climate models relative to the driving global climate models are also assessed. Although an encouraging increase in credibility and an improvement in the simulation of mean states, interannual variability, and past climate changes are visible in the progression from CMIP3 to CMIP5, some previously noticed biases such as the ridge position of the western North Pacific subtropical high and the associated rainfall bias are still evident in CMIP5 models. Weaknesses are also evident in simulations of the interannual amplitude, such as El Niño-Southern Oscillation (ENSO)-monsoon relationships. Coupled models generally show better results than standalone atmospheric models in simulating both mean states and interannual variability. Multi-model intercomparison indicates significant uncertainties in the future projection of climate change, although precipitation increases consistently across models constrained by the Clausius-Clapeyron relation. Regional ocean-atmosphere coupled models are recommended for the dynamical downscaling of climate change projections over the East Asia-western North Pacific domain.

1. Introduction

Climate models are useful tools in understanding the mechanisms of climate variability and in predicting and projecting future climate change. Due to the limitations of current state-of-the-art climate models in representing physical processes, uncertainties exist in the simulation results of climate models. A multi-model ensemble is a useful way to reduce the uncertainties of individual models. The Coupled Model Intercomparison Project (CMIP) is an international community-based infrastructure in support of climate model intercomparison and climate change projection. Its most recent phase is CMIP-Phase 5 (CMIP5) [1,2]. The robustness of analysis of CMIP5 models has attracted an increasing amount of attention in recent years. The objective of the current study is to provide an overview of the performance of CMIP5 models over the East Asia-western North Pacific (EA-WNP) domain based on the published literature. The strengths and weaknesses of the models are assessed. This robust analysis aims to provide a useful reference on the creditability of CMIP5 models, and should assist in model development and improvement.

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2. Climate mean state simulation

Benefiting from improvements in climate models in the past five years, the basic climatological features over the EA-WNP domain are reasonably simulated by the CMIP5 models [3]. For example, both the summer monsoon rainfall pattern and 850 hPa wind fields are reproduced well by the CMIP5 atmospheric models. The skill score of precipitation simulation has slightly improved, from 0.75 (CMIP3) to 0.77 (CMIP5), in the multi-model ensemble (MME) [4]. The improvements in precipitation simulation are closely related to the improvements in atmospheric circulation simulation. The CMIP5 atmospheric models successfully reproduce the climatological low-level southerly wind and high-level westerly jet over East Asia [5,6]. A large spread is seen among models in the simulation of large-scale circulations [7]. Nearly all CMIP5 models show a northward shift of the western North Pacific subtropical high (WNPSH), which leads to bias in the East Asian summer monsoon (EASM) rainfall band simulation [4,8].

The CMIP5 models are more skillful than the CMIP3 models in the simulation of the EA-WNP climate [9], although both CMIP3 and CMIP5 models produce slightly less precipitation than the observed [10]. This is evident in the pattern of summer monsoon rainfall, circulation, moisture transportation, and mid-tropospheric horizontal temperature advection [11], as well as in simulations of the onset of the summer monsoon [12,13]. The extension of the monsoon rain band over East Asia is underestimated, whereas the rainfall over the subtropical western/central Pacific Ocean is overestimated. Although the bias of the northward shift of the WNPSH ridgeline is also evident in CMIP3 models [14], coupled models general show better results than the standalone atmospheric models in the CMIP5 [6].

3. Interannual climate variability

The WNPSH is an important part of the EASM system. It has two dominant modes on the interannual time scale [15]. Both modes correspond to an anomalous anticyclone over the western North Pacific, but the anticyclone associated with the second mode is shifted northward relative to the one associated with the first mode [16]. He and Zhou [8] showed that the first mode is associated with sea surface temperature (SST) anomalies in the tropical Indian Ocean and central-eastern Pacific, while the second mode is associated with local SST anomalies. The first mode can be reproduced well by the CMIP5 Atmospheric Model Intercomparison Project (CMIP5-AMIP) simulations, indicating that it is a forced mode. However, the second mode cannot be perfectly simulated by the CMIP5-AMIP simulations. The simulated anomalous anticyclone in the MME or most individual models is far weaker than what is observed. This suggests that the second mode is associated with air-sea interactions over the tropical western North Pacific. There is substantial covariability between the WNPSH and the North Pacific subtropical high [17].

The EA-WNP monsoon is tightly linked with El Niño through a key low-level anomalous anticyclone over the tropical western North Pacific (the western North Pacific anomalous anticyclone, or WNPAC) [18]. The WNPAC is maintained over three consecutive seasons, from the El Niño mature winter to decaying summer [19]. Model performances in simulating the El Niño-Southern Oscillation (ENSO)-monsoon relationship are determined by their skill in simulating the WNPAC [20].

During an El Niño mature winter, the southwesterly anomalies to the northwestern flank of the WNPAC weaken the mean northeasterly wind of the East Asian winter monsoon [21]. Meanwhile, they transport moisture northward to Southeast China, greatly increasing the precipitation there [22]. About half of the CMIP5 coupled general circulation models (CGCMs) can reasonably simulate the WNPAC during an El Niño mature winter. However, nearly all models underestimate the positive precipitation anomalies over Southeast China [20].

WNPAC not only influences the East Asian winter monsoon (EAWM), but also modulates the temporal evolution of El Niño. The easterly anomalies on the southern flank of the WNPAC tend to stimulate oceanic upwelling Kelvin waves and thus accelerate the decay of El Niño [23,24]. The western North Pacific anomalous cyclone (WNPC), the counterpart of WNPAC during a La Niña winter, tends to be shifted westward relative to the WNPAC. Correspondingly, the westerly anomalies over the equatorial western Pacific during a La Niña winter are far weaker than the easterly anomalies during an El Niño winter. As a result, La Niña tends to decay much more slowly than El Niño [24]. This mechanism is supported by the results of the CMIP5 CGCMs. If a model can (or cannot) simulate the asymmetry between WNPAC and WNPC, it can (or cannot) simulate the asymmetry in evolution between El Niño and La Niña [20].

During an El Niño decaying summer, the WNPAC is maintained by the combined effects of local cold SST anomalies and remote forcing from the tropical Indian Ocean [25]. The CMIP5-CGCM MME supports the argument that the WNPAC and local cold SST anomalies form a damping coupled mode. The cold SST anomalies can only suppress local convection and thus maintain the WNPAC in the early summer, before they are damped completely by local negative feedbacks [20]. During the late summer, the maintenance of the WNPAC is primarily related to remote forcing from the tropical Indian Ocean through atmospheric Kelvin wave dynamics [25–27]. The CMIP5-CGCM MME indicates that the remote-forcing effect of the tropical Indian Ocean on the WNPAC is gradually enhanced with the establishment of the climatological monsoon trough from July to August [20].

Song and Zhou [4] systematically compared the CMIP5-AMIPs with the CMIP3-AMIPs in their simulations of the WNPAC and of the associated negative precipitation anomalies over the western North Pacific and positive precipitation anomalies extending from the middle and lower reaches of the Yangzi River to Japan. The CMIP5-AMIPs show higher capability and thus an improved simulation of the interannual pattern of the EASM (Fig. 1) [4]. The CMIP5-CGCMs have higher capability than the corresponding AMIP runs in their simulations of the WNPAC due to stronger remote forcing from the tropical Indian Ocean in the coupled models; this suggests that air-sea interactions are essential in simulating the interannual variability of the EASM [6].

4. Past climate change simulation

Past climates provide an opportunity to establish constraints for East Asian monsoon (EAM) evolution and dynamics. Looking at geological analogues, the most recent warm climate associated with carbon dioxide (CO_2) values ((405 ± 50) ppm) that are higher than those of the modern climate is the mid-Pliocene (MP); therefore, the MP is considered as the potential analogue for understanding the future warming climate. For example, the MP Hadley circulation is regarded as a potential analogue for the future scenario [28–30]. For North China, the simulated EAM in the MP is demonstrated as an intensified EASM and as a weakened EAWM [31–33]. Both the simulated EASM and EAWM in the MP agreed reasonably well with geological reconstructions. The enhancement of the land-sea thermal contrast contributes to the intensified EASM in the MP [33]. The intensified EASM circulation brings stronger moisture transport into the East Asian domain, by increasing the local convergence of the stationary meridional velocity, resulting in an increase of the MP EASM precipitation in both the atmospheric general circulation model (AGCM) and the CGCM simulations [33].

The decadal-centennial variations of the EASM during the last