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UNDERSTANDING THE ASIAN SUMMER MONSOON RESPONSE TO GREENHOUSE WARMING: THE RELATIVE ROLES OF DIRECT RADIATIVE FORCING AND SEA SURFACE TEMPERATURE CHANGE

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1. INTRODUCTION

Regional climate information under global warming is urgently needed for climate adaptation and socio-economic planning in various sectors, such water resources, agriculture and public health, particularly for the densely populated Asian monsoon regions (e.g. Kumar et al. 2004). However, future hydroclimate projections from state-of-the-art climate models show large uncertainty and model discrepancy, particularly over the monsoon regions (Turner and Annamalai 2012). It is important to understand the different physical pathways by which greenhouse gases (GHGs) may impact regional hydroclimate and distinguish those from the uncertainty caused by low model skill.

The Asian summer monsoon is projected to enhance under greenhouse warming, dominated by the thermodynamic "wet-get-wetter" mechanism (Held and Soden 2006). On the other hand, dynamical changes related to atmospheric circulation are relatively weak (Li et al. 2015). This weak and diverging circulation response may contribute largely to the uncertainty in monsoon rainfall projections.

The response to rising GHGs can be through both direct radiative effect and indirect effect via sea surface temperature (SST) warming. Recent studies have shown that the two may cause different responses in tropical circulation (He and Soden 2015), summertime Pacific anticyclone (Shaw and Voigt 2015), and midlatitude jets (Grise and Polvani 2014). The relative importance of the direct and indirect effects may result in discrepancies in conclusions.

In this study, regional hydroclimate responses to greenhouse warming are assessed using a set of climate model simulations uncluding coupled model projections for the 21st century and idealized atmosphere-only climate change experiments with prescribed atmospheric conditions and SSTs. The purpose of this study is to distinguish the relative roles of atmospheric radiative forcing and ocean-atmosphere interactions, and address the arising uncertainties in model projections.

2. DATA AND METHODS

2.1 *Coupled model simulations and idealized experiments*

For coupled model simulations, we used monthly output of 35 Coupled Model Intercomparison Project - Phase 5 (CMIP5) models under the high-end representative concentration pathway 8.5 (rcp8.5) emission scenario. For idealized experiments, we used outputs from 10 models of the Atmospheric Model Intercomparison Project (AMIP) experiments. The following experiments were used: 1) the control simulation (CTRL), run with observed SST and sea ice concentration from 1979 to 2008; 2) quadrupling CO2 radiative forcing experiment (4xCO2), same SST and sea ice as CTRL, but with quadrupled atmospheric CO2 concentration; 3) uniform 4K warming experiment (+4K), same CO2 concentration as CTRL, but adding a uniform +4K SST anomaly globally. The direct (indirect) response is quantified as the difference of the 30-year climatology between 4xCO2 (+4K) and CTRL.

2.2 *Moisture budget analysis*

We use the atmospheric moisture budget equation to analyze the changes in the hydrological cycle, following Li et al. (2015). In steady state, precipitation minus evaporation (P-E) balances the convergence of the vertically integrated atmospheric moisture flux, which can be separated into contributions of mean moisture convergence and transient eddies. The mean moisture convergence term is further separated into thermodynamic and dynamic components, involving only changes in moisture and circulation, respectively.

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3. RESULTS

3.1 *Precipitation response to future GHG forcing*

The future total rainfall response to increasing CO2 is a combination of direct radiative forcing and indirect SST change. The two effects exert significantly different responses both over the land and ocean (Fig. 1). While the direct radiative effect (Fig. 1a) dries the ocean globally, SST warming (Fig. 1b) dominates the total response with strongly enhanced wetting. The land rainfall response displays significant regional variations in both the direct and indirect responses. The combination of the two effects (Fig. 1c) generally captures the large-scale pattern in the coupled model response (Fig. 1d). For the Asian monsoon, the direct radiative effect dominates monsoon rainfall change through enhanced wetting over most regions in China and India; the indirect SST change dries eastern China and northern India, but has a strong wetting over central and southern India, along with a large model spread.

3.2 *Thermodynamic and dynamic mechanisms of CO2-induced rainfall change: direct radiative forcing versus indirect SST effect*

We further analyze the thermodynamic and dynamic mechanisms contributing to the differing precipitation responses of the direct and indirect effects. The precipitation change is predominantly driven by the mean moisture flux convergence over the monsoon regions, with transient eddies playing a lesser role (not shown). As show in Fig. 2 for India (a) and eastern China (b), the thermodynamical change is dominated by the strong enhanced wetting due to SST warming (blue), with little change related to direct radiative forcing (red). The dynamical change show distinct opposing responses over the Asian monsoon region: direct radiative effect enhances monsoon circulation while SST warming weakens the circulation. Due to this cancelation, the dynamical component in the rcp8.5 (black) multi-model mean response is very weak along with large inter-model discrepancy.

3.3 *Understanding uncertainties in future monsoon projections*

The competing effect of direct radiative forcing and indirect SST warming on monsoon circulation has important implications for the uncertainty in future projections. While the thermodynamical response is robust across the models and well understood, there is substantial uncertainty in both the magnitude and the sign of the dynamical changes. The lack of consensus among the models and weak multi-model mean responses may result from the multiple physical processes evolving on different time scales as well as differences in model skill. Understanding the physical mechanisms underlying the change to different forcings is essential towards constraining the uncertainties in regional climate prediction.

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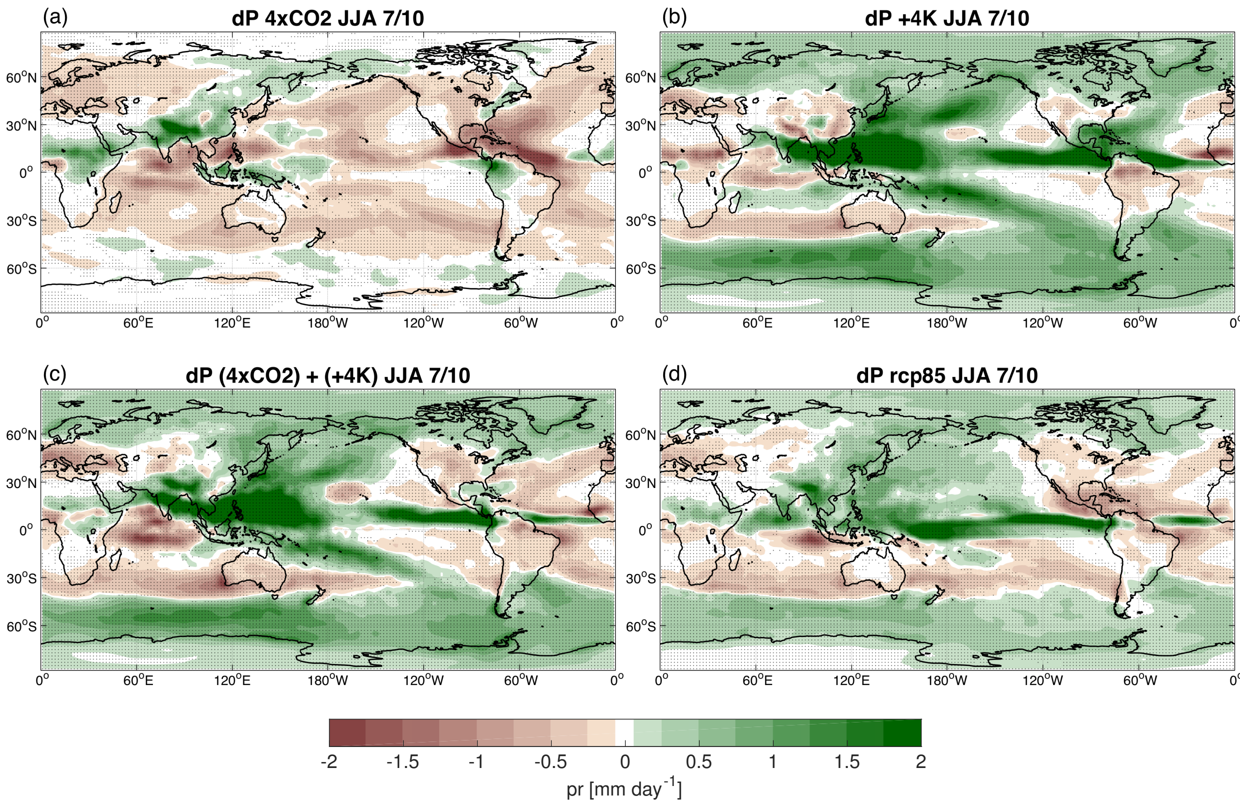

Fig. 1 Precipitation response for (a) 4xCO2, (b) +4K, (c) 4xCO2 plus +4K, and (d) rcp8.5. Stippling denotes 7 out of 10 models agree on the sign of change. Units are mm/day.

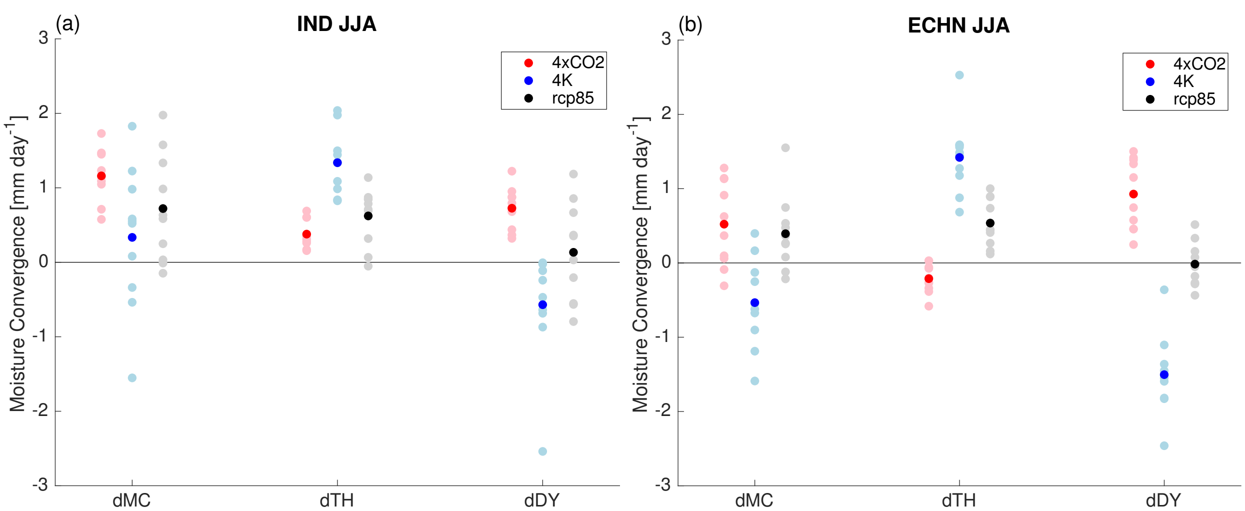

Fig. 2 Area averaged changes of the mean moisture convergence (dMC), the thermodynamic component (dTE), and the dynamic component (dDY) over (a) India and (b) East China for (red) 4×CO2, (blue) +4K, and (black) rcp8.5. The dark-colored dots show multi-model means, and the light-colored dots show individual models. Units are mm/day.