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Changes in Seasonality in China under Enhanced Atmospheric CO_2 Concentration

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Abstract Seasonality changes in China under elevated atmospheric CO_2 concentrations were simulated using nine global climate models, assuming a 1% per year increase in atmospheric CO_2. Simulations of 20th century experiments of season changes in China from the periods 1961–80 to 1981–2000 were also assessed using the same models. The results show that the ensemble mean simulation of the nine models performs better than that of an individual model simulation. Compared the mean climatology of the last 20 years in the CO_2-quadrupling experiments with that in the CO_2-doubling ones, the ensemble mean results show that the hottest/coldest continuous-90-day (local summer/winter) mean temperature increased by 3.4/4.5°C, 2.7/2.9°C, and 2.9/4.1°C in Northeast (NE), Southwest (SW), and Southeast (SE) China, respectively, indicating a weakening seasonal amplitude (SA), but by 4.4/4.0°C in Northwest (NW) China, indicating an enlarging SA. The local summer lengthened by 37/30/66/54 days in NW, NE, SW, and SE China, respectively. In some models, the winter disappeared during the CO_2-quadrupling period, judging by the threshold based on the CO_2-doubling period. The average of the other model simulations show that the local winter shortened by 42/36/61/44 days respectively, in the previously mentioned regions.

Keywords: seasonality in China, global warming, scenario, CO_2-increase experiment

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1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), most of the observed increase in the global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic concentrations of greenhouse gases (GHGs). The enhanced greenhouse effect is believed to have caused the observed warming at the continental scale, based on the standard optimal detection methodology (Stott, 2003). However, regional changes in seasonal patterns of temperature under global warming remain unclear. Many studies have applied certain temperature thresholds to investigate changes in seasonality dealing, for example, with the growing season (Christidis et al., 2007), frost-free season (Kunkel et al., 2004), and climatic spring onset (Qian et al., 2009), all of which are critical for ecosystems. However, Stine et al. (2009) argued that the threshold-based definitions conflate changes in the phase of the annual cycle and changes in the annual mean and suggested investigating the amplitude and phase of the yearly -period sinusoidal component separately. They found that the seasonal phase over extra-tropical land has shifted towards that of earlier seasons by 1.7 days, with significant changes in the seasonal amplitude during 1954–2007. Changes in seasonality have also been studied in China. Yan et al. (2001) pointed out a weakening seasonal cycle under the recent warming trend, as the warming was more prominent in the winter than the summer. Zhang (1934) proposed a pentad-mean temperature of 10°C and 22°C, as threshold temperatures for winter and summer, respectively, in China. Miao and Wang (2007) studied this and found that in most of China, the summer period lengthened and the winter period shortened during 1951–2005. Yan et al. (2011) studied the local summer and winter to investigate the changes in seasonality in China. They found that the local summer lengthened by 2–4 days, while the winter shortened by 2–6 days per decade during the period 1960–2008; the summer mean temperature increased by 0.1–0.2°C while the winter temperature increased by 0.2–0.4°C per decade over almost all of China. Thomson (1995) examined the Central England temperature-time records (1659–1990) and concluded that the changes in seasonal phase may be associated with increases in atmospheric CO_2 concentrations.

Having investigated changes in seasonalality with updated observations in China (Yan et al., 2011), the present authors tried to quantify possible future changes using simulations of the doubling and quadrupling CO_2 experiments adopted by IPCC (2007). Methods and data used are explained in Section 2. The results are presented in Section 3. Conclusions are summarized with a discussion in Section 4.

2 Data and methods

2.1 Data

The homogenized daily mean surface air temperature

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(SAT) series at 541 stations in China during the period 1961–2000, developed by Li and Yan (2009) using the Multiple Analysis of Series for Homogenization (MASH) method (Szentimrey, 1999, 2008), were applied to evaluate observed changes in seasonality in China.

The daily-mean near-surface (two-meter) air temperature datasets obtained from the 1% per year CO_2 increase experiments adopted by IPCC AR4, were used to investigate the changes in seasonality of temperature in China induced by enhanced atmospheric CO_2 concentration. These experiments are under the 1% per year CO_2 increase scenario as well as under doubled and quadrupled CO_2 conditions. Datasets of the last 20 years of each simulation are used in this analysis. As the outputs of other IPCC models are incomplete, only nine models were used, i.e., the third generation coupled global climate model (3.1, T47) of Canadian Centre for Climate Modeling & Analysis (CCCMA-CGCM3.1 (T47)), coupled model (3.0) of Centre National de Recherches Meteorologiques, Meteo France, France (CNRM-CM3), coupled model (2.0, 2.1) of Geophysical Fluid Dynamics Laboratory, the National Oceanic and Atmospheric Administration (NOAA) (GFDL-CM2.0, GFDL-CM2.1), ModelE-Russell of Goddard Institute for Space Studies, the National Aeronautics and Space Administration (NASA), USA (GISS-MODEL-ER), the fourth-generation European Centre Hamburg atmospheric general circulation Model (ECHAM4) model of Istituto Nazionale di Geofisica e Vulcanologia, Italy (INGV-ECHAM4), ECHAM4 + HOPE-G model of Meteorological Institute of the University of Bonn, Germany (MIUB-ECHO-G), ECHAM5 model of Max Planck Institute for Meteorology, Germany (MPI-ECHAM5), coupled global climate model (2.3.2a) of Meteorological Research Institute, Japan (MRI-CGCM2.3.2a), referred to thereafter as m1, m2, …, m9, respectively.

Simulations of 20th century experiments (20c3m, 1961–2000) using each model are compared with the observed data during the same period in order to assess the model's performance on predicting seasonality. Details of the experiments and models are available on http://www.pcmdi.llnl.gov/.

Overlooking the inter-annual climate variability at the regional scale, which cannot be reproduced well by current climate models, we used the average of Period I (1961–80) and Period II (1981–2000) to analyze the observed long-term change in seasonality, also because there is a major interdecadal transition in the late 1970s as well-known (e.g., Trenberth and Hurrell, 1994; Fedorov and Philander, 2000; Zhou et al., 2007). Table 1 summarizes the data used.

2.2 Methods for quantifying large-scale changes in temperature seasonality in China

There are two basic quantities for describing temperature seasonality, Seasonal Amplitude (SA), and Seasonal Phase (SP). The former can be defined as the temperature contrast between the two extreme seasons, i.e., the hottest/coldest continuous 90-day period (ESH/ESC).

To evaluate changes in SP, we define a couple of hot thresholds (HT) or cold thresholds (CT), i.e., the 20-year-average daily mean temperature on the beginning or end dates of the hottest or coldest continuous 90-day period in Period I. The local summer and winter temperatures for Period II are then determined if the daily temperature records continuously surpass HT or CT. The difference in the beginning or end dates between Period I and Period II are indicative of changes in SP.

Focusing on large-scale regional features of changes in seasonality, we divided China into four regions, using 35°N and 102°E as the boundaries: Northeast (NE), Northwest (NW), Southeast (SE), and Southwest (SW) China.

3 Results

3.1 Changes in SA in the 20c3m experiments

Figure 1 shows that the observed SA in Period II is weaker than that in Period I in NW and NE China, due to a larger temperature increment in ESC than in ESH. In SE China, there is a warming in ESC and a minor cooling in ESH, also leading to a weaker SA. However, the SA changes little in SW China, with almost same temperature increment in ESH and ESC.

In the 20c3m experiments, some of the nine models reproduced the observed changes in SA in the different regions. To quantify the performance of all the 20c3m simulations, two aspects are considered. The first is the direction of the changes in SA (weaker or stronger) simulated by models, and compared with observation data (Fig. 2a) in each region. Figure 2a shows that the results of model m7 and the mean of the nine models match well with the observations in three (NW, NE, and SW) out of four regions. Models m5 and m8 perform the worst in modeling SA changes in China.

The second aspect is the difference between simulation and the observation, as depicted in Fig. 1. Take '1' to indicate the simulated result that is the closest (out of ten results, including the ensemble mean) to the observation; '2' is the 2nd closest, and so on. The individual models may give better results than the ensemble mean for a region (Fig. 2b), but larger biases for other regions. By and

Table 1 Summary of the datasets used.

	Observations	Simulations	
		20c3m	1% CO_2 increase experiments
Period I	1961–80	1961–80	Doubling CO_2 (last 20 years of the simulation)
Period II	1981–2000	1981–2000	Quadrupling CO_2 (last 20 years of the simulation)

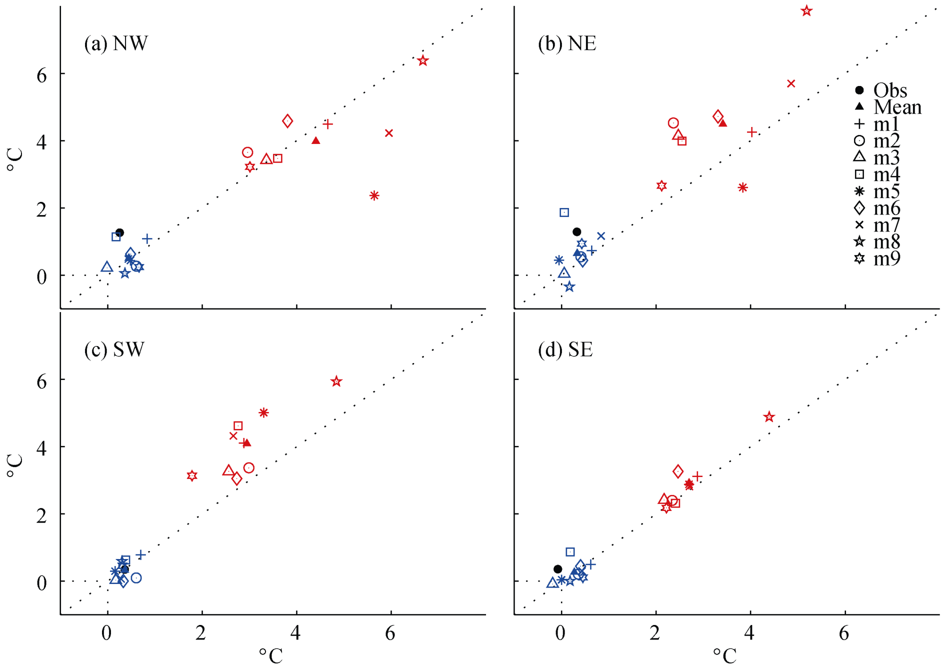

Figure 1 The temperature increments of ESH (*x*-coordinate) and ESC (*y*-coordinate) from Period I to Period II. Black points indicate the experimentally observed temperature. The blue points indicate the simulated results of the 20c3m experiments using nine models; red ones are the results between quadrupling- and doubling-CO_2 experiments. The solid-triangles indicate the mean of results obtained using the nine models.

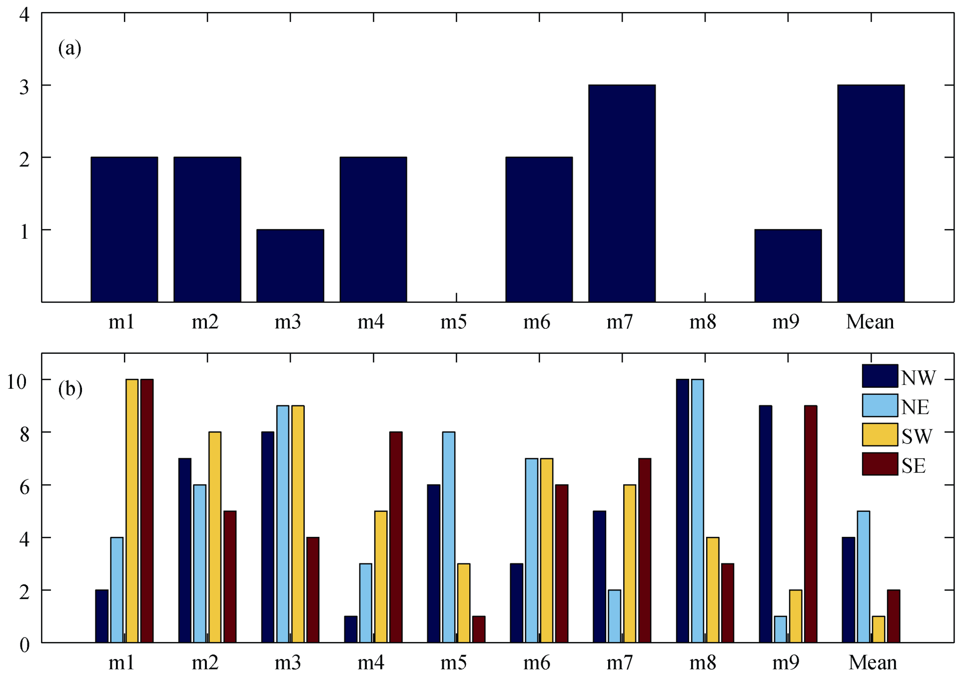

Figure 2 (a) Number of regions where the 20c3m experiment reproduced the observed changes in SA; (b) Difference between observed and simulated results, as defined in the text.

large, the ensemble mean has the smallest bias, implying that it could give more reasonable results than any individual model.

3.2 Changes in SP in the 20c3m experiments

From Period I to Period II, the observed local summer lengthened by an average of 3.8 days, while the winter shortened by 5.8 days in the four regions analyzed, mainly due to an earlier beginning date and a delayed end date (Figs. 3a and 3b). These results are consistent with those of Yan et al. (2011).

To assess the model's performance in predicting SP in China, we compare the observed and simulated changes in the beginning/end dates of local summer and winter for the four regions, a total of 16 pairs of quantities. The number of pairs with the same sign of change for each model is illustrated in Fig. 4a. The difference between the observation and simulation results, similar to that defined for SA, is shown in Fig. 4b.

As Fig. 4a shows, the ensemble mean of nine models simulations produces the best estimate, with 13 out of 16 SP-related quantities being of the same sign of change as the observed change (Fig. 4a). The simulation from m6 has the smallest difference from the observed changes in SP (most values are small and smallest box size). The ensemble mean gives the most stable results (without extreme values) of all the models (Fig. 4b).

In short, the simulations on changes in seasonality (as defined in this paper) in China using the current climate models, especially the ensemble mean results, show that the current climate models performed reasonably well in predicting seasonality changes.

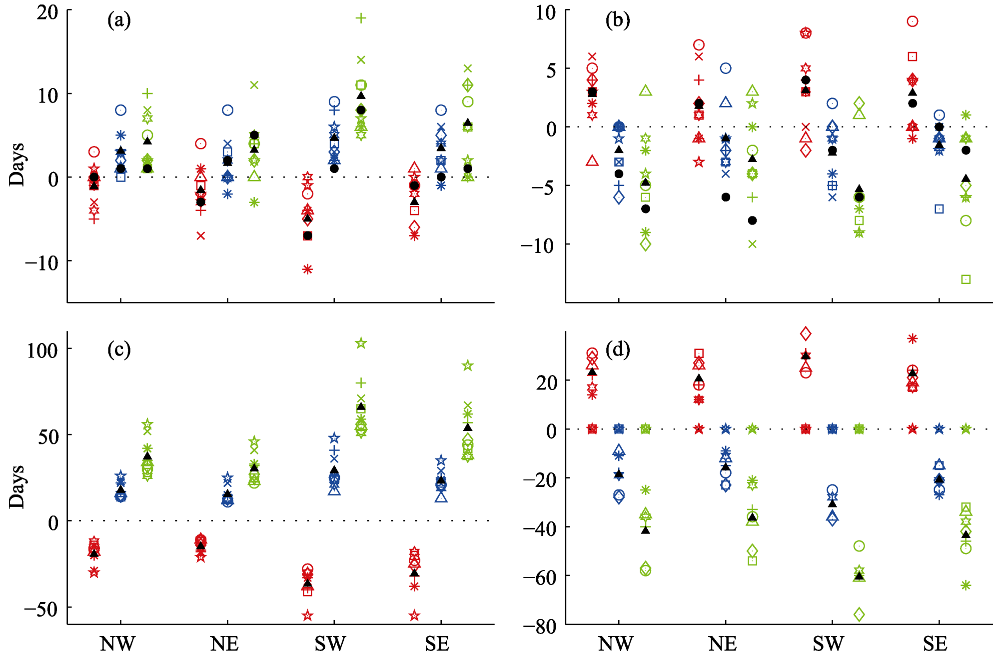

Figure 3 Changes in beginning dates (red), end dates (blue), and lengths (green) of local (a) summer/(b) winter between Period II and Period I in the 20c3m experiments; (c)/(d) are the same as (a)/(b) except for the doubling-to-quadrupling-CO_2 experiments. A positive value indicates delay of date or increase in length, while a negative value indicates an earlier date or decrease in length. The marks represent different models, ensemble mean, and observation as same as in Fig. 1.

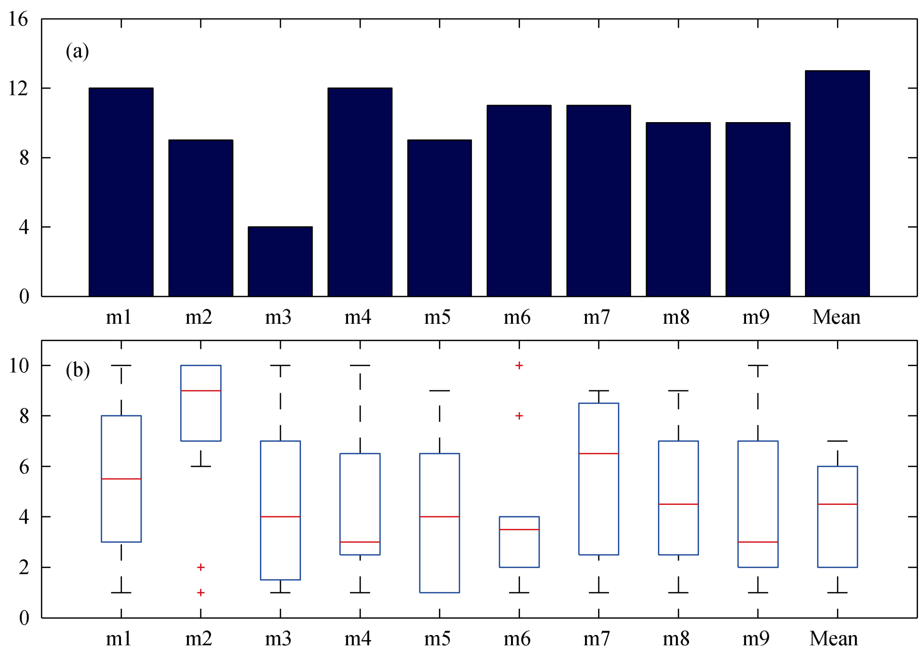

Figure 4 (a) Number of the regional SP-related quantities in China for which the simulated change in the 20c3m experiment is of the same sign as the observed change; (b) the box-and-whiskers distribution of differences between observation and simulation with regard to the 16 SP-related quantities in China (similar to that defined for SA in Fig. 2b). The bottom and top of the box are the 25th and 75th percentile (the lower and upper quartiles, respectively), and the band near the middle of the box is always the 50th percentile (the median). The black bands are within 1.5 inter quartile range (IQR) of the lower/upper quartile, and the red '+' is the extreme value.

3.3 Changes in seasonality from doubling to quadrupling CO_2

Figure 1 shows that the temperature increments from Period I to Period II in the 1% per year CO_2-increase experiments are much larger than that in the 20c3m experiments. Most of the nine models project that in NE, SW, and SE China, there is a weaker SA in Period II (Quadrupling CO_2) than in Period I (Doubling CO_2), due to a greater positive temperature increment in ESC than in ESH. The average temperature increments of nine models are 3.4/4.5°C, 2.7/2.9°C, and 2.9/4.1°C (ESH/ESC), respectively. NW China is an exception. Seven out of nine models simulate very close to no change or slightly weaker of SA (Fig. 1a), but with an average temperature increment (nine models) of 4.4/4.0°C for ESH/ESC, indicating a greater SA. This implies large uncertainty in simulating seasonality in this desert area possibly due to problems in current land-surface process models for desert. Hence, the 'enlarged SA' in NW China is doubtful, though it may be a regional feature under global warming.

Figures 2c and 2d show that, in the 1% per year CO_2-increase experiments, the beginning dates and end dates of local summer of the four regions are of the same sign of as change and a much larger change than that in the 20c3m experiments. All models project longer summer season and the local summer lengthens by 37/30/66/54 days based on the ensemble mean results for NW/NE/SW/SE China, respectively. In some model simulations (e.g. m7, m8 for all the four regions; m4 for regions NW and SW; m5 for region SW), the local winter disappears in Period II, based on the threshold defined in Period I. The average of other models' simulations shows that local winter shortens by 42/36/61/44 days for the four regions, respectively.

4 Conclusions

This work reports a brief assessment of current climate models' performance on reproducing changes in seasonality in China, and on projecting changes under the 1% per year CO_2 increase scenario as well as under doubled and quadrupled CO_2 conditions. The main conclusions are as follows.

The ensemble mean simulation is more reliable than individual models' with regard to the observed changes in seasonality in China during the late 20th century.

The ensemble mean results suggest that from doubling to quadrupling CO_2, the local extreme hot/cold seasons are warmer by 4.4/4.0°C, 3.4/4.5°C, 2.9/4.1°C, and 2.7/2.9°C in NW, NE, SW, and SE China, respectively. These indicate a weaker SA in NE, SW, and SE, but a larger SA in NW China.

In the 1% per year CO_2 increase experiments, the local summer lengthens by 37/30/66/54 days (based on the average results of the nine models) for NW/NE/SW/SE China, respectively. In some models (e.g. m7, m8 for all the four regions; m4 for regions NW and SW; m5 for region SW), the local winter disappears if the atmospheric concentration of CO_2 is doubled or quadrupled. The average of other models' results shows that the local winter shortens by 42/36/61/44 days for NW/NE/SW/SE China, respectively.

Assessing model performance in comparison to observations is essential for judging the reliability of projections under enhanced-CO_2 scenarios. Our results suggest that each of the current climate models may not be good enough in reproducing observed changes in seasonality at the regional scale, but the ensemble mean results are reasonably good. Nevertheless, the present work did not stress on the changes between the observed periods, but those between doubled and quadrupled CO2 scenarios. It is also worthwhile noting that the projected changes in seasonality in China with doubling or quadrupling CO_2 levels may be regarded as a reference of climate changes in seasonality in this region under a forced condition 'purely' associated with enhanced atmospheric CO_2 concentration. A more reasonable estimate of climate change should involve interdecadal variations, which are considerable, particularly in this region and are somehow missed by most current climate models.

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