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Impacts of a nuclear war in South Asia on rice production in Mainland China

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Abstract A regional nuclear war between India and Pakistan with a 5 Tg black carbon injection into the upper troposphere would produce significant climate changes for a decade, including cooling, reduction of solar radiation, and reduction of precipitation, which are all important factors controlling agricultural productivity. We used the Decision Support System for Agrotechnology Transfer agricultural simulation model to simulate regional nuclear war impacts on rice yield in 24 provinces in China. We first evaluated the model by forcing it with daily weather data and management practices for the period 1980–2008 for 24 provinces in China, and compared the results to observations of rice yields in China. Then we perturbed observed weather data using climate anomalies for a 10-year period from a nuclear war simulation. We perturbed each year of the 30-year climate record with anomalies from each year of the 10-year nuclear war simulations for different regions in China. We found that rice production would decline by an average of 21 % for the first 4 years after soot injection, and would slowly recover in the following years. For the next 6 years, the reduction in rice production was about 10 %. Different regions responded differently to climate changes from nuclear war. Rice production in northern China was damaged severely, while regions along the south and east coasts showed a positive response to regional nuclear war. Although we might try to adapt to a perturbed climate by enhancing rice planting activity in southern and eastern China or increasing fertilizer usage, both methods have severe limitations. The best solution to avoid nuclear war impacts on agriculture is to avoid nuclear war, and this can only be guaranteed with a nuclear-weapon-free world.

1 Introduction

Although the global nuclear arsenal has fallen by more than a factor of three since the 1980s, after realizing that "nuclear winter" would be a catastrophic consequence of a nuclear war between superpowers (e.g., Turco et al. 1983), society is still facing a potential nuclear

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disaster due to the rising number of small nuclear powers. Besides the direct effects of explosions, radioactivity, and fires, indirect effects from the climate response to long-lasting smoke could bring a colder, drier, and darker world for years (Robock et al. 2007a; Robock et al. 2007b; Toon et al. 2007), with enhanced ultraviolet flux due to ozone destruction (Mills et al. 2008). Modeling work showed that a regional conflict between India and Pakistan using 100 Hiroshima-size bombs could reduce global-average surface short wave radiation by 15 W m^{-2}, surface temperature by 1.5°C, and precipitation by 0.3 mm/day in the first and second years after a 5 Tg black carbon injection from the fires into the upper troposphere, and would produce large stratospheric ozone depletion even 3 years after the event (Mills et al. 2008; Robock et al. 2007b). Those nuclear war impacts on climate could last for 10 years, with a slow recovery. Since agriculture is one of the human activities most dependent on climate, those climate changes due a small regional nuclear war could significantly influence agricultural productivity in regions far from the conflict.

There have been extensive studies on climate change impacts on food production by analyzing historical records (e.g., Lobell et al. 2008; Lobell and Field 2007; Lobell et al. 2011; Tao et al. 2008; Tao et al. 2006; Peng et al. 2004) and using dynamic crop models (e.g., Rosenzweig and Parry 1994; Adams et al. 1990; Yao et al. 2007; Tao and Zhang 2011). It is clear that climate change will affect the productivity of different crops, but the actual effect depends on the combination of regional climate and agricultural practices, even for the same crop species. For example, according to observations, rice yield would decline by 15 % for each 1°C increase in the growing season mean temperature in the Philippines (Peng et al. 2004), while in China a 1°C increase of temperature leads to a 2 % increase in rice yield (Lobell et al. 2011). Since regional nuclear war affects regional climates in different ways, and climate changes due to a nuclear war are significant enough to affect agriculture productivity, it is important to investigate crop responses to nuclear war in different regions.

Harwell and Cropper (1989) investigated nuclear war impacts on global agricultural production by analytical, historical, statistical, and physiological analysis approaches and also studied wheat and barley production change in Canada using a simulation model. Recently, Özdoğan et al. (2012) simulated the effects of the same nuclear war scenario (Robock et al. 2007b) on soy and corn production in four states in the Midwest United States using the Agro-IBIS model (Kucharik 2003; Kucharik and Twine 2007) and found reductions of 10–20 % in soy and maize crop production for a decade. Here we investigate the impacts on a different crop in a different region of the world using a different crop model. In the future, more comprehensive studies will be needed to see how robust these results are.

This study focuses on regional nuclear conflict impacts on single cropping rice production in Mainland China. "Single cropping rice" has one cultivation cycle per year. There is also "double cropping rice," including double cropping early rice and double cropping late rice. China is the largest rice production country in the world and accounted for 28 % of world rice production in 2008 (FAO 2010). Because of its northern mid-latitude continental location, China would experience reductions of temperature, solar radiation, and precipitation, even from a nuclear conflict elsewhere (Cropper and Harwell 1989; Robock et al. 2007b). Those climate perturbations would damage rice growth and significantly affect the food supply in China. Since rice is an important source of calories (~27 %) for the Chinese, and the domestic supply is dominant (FAO 2010, 2011), any climate change affecting rice production could trigger major changes in the economy in China and in the world trade system.

In this study, we address two questions: (1) How would regional nuclear conflict affect rice production in Mainland China? and (2) Would there be a way to adapt to this catastrophe, even though none of us would expect it to occur?

2 Methodology

2.1 Crop model - DSSAT

Crop simulations in this study use the Decision Support System for Agrotechnology Transfer (DSSAT) model version 4.5 (Jones et al. 2003). This dynamic biophysical crop model simulates crop growth on a per hectare basis, maintaining balances for water, carbon and nitrogen. It requires information about the plant environment (weather, CO_2, and soil), cultivar genotype, and agricultural management practices. The outputs from this model are potential yields, which are usually higher than actual yields (Yu et al. 2010).

Before examining nuclear war impacts on rice yields in China, we evaluated DSSAT in 24 provinces or autonomous regions or municipalities (in the rest of the paper, referred to as provinces) for rice, considering weather (daily maximum temperature, daily minimum temperature, daily precipitation and daily solar radiation), soil, cultivar, fertilizer, and the carbon dioxide enrichment effect. The evaluation results are shown in Section 3.1.

2.2 Observations in China

Chinese weather data are from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). There are 148 weather stations evenly distributed over Mainland China, except Tibet and Shanxi. Weather observations include daily maximum temperature, daily minimum temperature, daily average temperature, daily precipitation, and daily solar duration from January 1978 to December 2008 in 30 provinces, and to December 2007 in another two provinces. Since crop simulation was conducted on a province-by-province basis, we used one representative weather station for each province to conduct further simulations, for a total of 24 weather stations (Table 1). Soil profile information is from the World Soil Information Database (Batjes 2008, 2009). In total, there are 61 recorded soil profiles in China with physical and chemical properties from the surface to around 100 cm. We used soil types similar to surrounding provinces to fill in a few missing soil profiles. Agricultural data are from the Chinese Agriculture Year Book (Ministry of Agriculture of the People's Republic of China 2009), which provides yields, productions and planting areas of rice from 1980 to 2008.

2.3 Climate forcing data

Climate forcing of simulated regional nuclear war is from Robock et al. (2007b). They used the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE atmosphere–ocean general circulation model (GCM) to simulate a regional nuclear conflict between India and Pakistan with 5 Tg black carbon injected into the upper troposphere. The event occurred on May 15, and the simulation lasted for 10 years. Anomalies of monthly averages of surface temperature, solar radiation, and precipitation at each location were extracted to perturb daily observations (see details in Section 2.4). We used the simplest method to downscale the monthly average to daily values: anomalies of monthly average temperature and solar radiation were uniformly added to observed daily maximum temperature, daily minimum temperature, and daily solar radiation; the anomaly of monthly average precipitation was divided by the observed monthly average precipitation, and daily precipitation was changed by that fraction on each day when precipitation occurred.

Table 1 Location information and agriculture management used in DSSAT simulations. Numbers refer to province locations in Fig. 5

No.	Province	Latitude (°N)	Longitude (°E)	Altitude (m)	Cultivar[a]	Fertilizer (kg/ha)[c]
1	Anhui	31.9	117.2	28	XY63	187 (131–216)
2	Beijing	39.8	116.5	31	G14	129 (74–172)
3	Fujian	26.7	118.2	126	WY35	142 (94–182)
4	Guangdong	24.7	113.6	61	XY2	188 (143–257)
5	Guangxi	22.0	108.6	15	XY99	127 (83–181)
6	Guizhou	26.6	106.7	1224	YG136	129 (74–171)
7	Hainan	20.0	110.3	64	XY99	156 (74–282)
8	Hebei	40.4	115.5	537	G14	128 (90–141)
9	Heilongjiang	44.6	129.6	241	IR 58[b]	85 (34–117)
10	Henan	36.1	114.4	76	G14	130 (66–213)
11	Hubei	30.3	109.5	457	G14	217 (106–286)
12	Hunan	26.2	111.6	173	GY22	119 (83–169)
13	Jiangsu	34.3	117.2	41	G14	175 (129–223)
14	Jiangxi	27.1	114.9	71	G14	94 (41–130)
15	Jilin	45.1	124.9	136	G14	120 (74–168)
16	Liaoning	42.4	122.5	79	G14	132 (92–173)
17	Neimenggu	43.6	118.1	799	IR 58[b]	95 (65–152)
18	Ningxia	38.5	106.2	1111	IR 58[b]	130 (105–156)
19	Shandong	37.5	117.5	12	G14	142 (55–213)
20	Shaanxi	33.1	107.0	510	GY22	115 (90–149)
21	Sichuan	32.1	108.0	674	GY22	141 (117–162)
22	Tianjin	39.1	117.1	13	G14	137 (63–207)
23	Yunnan	25.1	101.3	1301	YG136	155 (114–197)
24	Zhejiang	29.0	118.9	82	G14	116 (54–188)

[a] Yao et al. (2007)

[b] DSSAT genotype database

[c] Mean and range (1978–2008)

2.4 Experiments

To predict the impact of weather anomalies from a regional nuclear war on agriculture, a control climate first needs to be defined. Agriculture would respond differently with the same anomalies applied to different climate scenarios. In this study, we tested 30 climate conditions (observations for 1978–2007) for each year of the nuclear war simulation. There are 10 1-year climate anomalies (monthly average temperature, solar radiation and precipitation) from the regional nuclear conflict simulation, and those anomalies from each year were used to perturb each of the 30 years of observations. Therefore, for each year of the nuclear war event, there are 30 simulations of rice growth in 24 provinces in Mainland China. In total, there are 300×24 simulations.

In both control runs and nuclear event impact runs, but not in the evaluation runs, the agricultural practice was fixed to remove its impacts on crop yield. Rice was planted on March 25 along with 150 kg/ha fertilizer applied, and the rice was harvested at maturity. No irrigation was applied, to emphasize the influence of precipitation reduction. To exclude the carbon dioxide enrichment effect, we used a constant carbon dioxide concentration of 380 ppm.

3 Results and discussion

3.1 DSSAT evaluation

We evaluated the DSSAT model by using the available rice yield record in 24 provinces from 1980 to 2008. Information for the 24 sites is listed in Table 1, as well as the DSSAT settings used for evaluation. Monthly carbon dioxide concentrations were from Mauna Loa observations (Keeling et al. 1976; Thoning et al. 1989; updated from http://www.esrl.noaa.gov/gmd/ccgg/trends/). We assumed that from 1990 to 2008, rice used no more than 70 % of the annual fertilizer used in each province (Ministry of Agriculture of the People's Republic of China 2009). For the earlier period, 1980–1989, first we linearly extrapolated fertilizer use backwards using the data we had and then adjusted the amount slightly to fit the overall rice yield trend. In all simulations, previous crop residual and manure were not applied, and no pest stress has been considered. Since rice in China is irrigation-fed, the auto-irrigation function was turned on during the evaluation process at each location.

The model was able to simulate rice yield reasonably well (Fig. 1). The coefficient of determination, R^2, between observations and simulation in all 24 provinces is 0.76 (Fig. 1a). There were a few observations with extremely low values, but they were not used in our simulation. Since the weather conditions in those years were normal, those values would have been because of a reporting error or switch to a new agricultural practice. Figure 1 also shows time series of rice yield in the five major rice production provinces. Our simulations fit the observations quite well in terms of upward trend, average and standard deviation. The upward trend of observed rice yield was mainly caused by fertilizer, pesticide, irrigation, and CO_2 concentration changes according to a principal factor analysis (not shown).

3.2 Rice production reduction under regional nuclear conflict

Regional nuclear conflict in South Asia would reduce rice production in Mainland China. Rice production was calculated by multiplying rice yield by the rice planting area in 2008. Averaging 30 simulations for each nuclear war year, the reduction of rice production summed for the 24 provinces ranges from 5 Mt to 26 Mt (5 %–27 %), with the largest reduction in year 1 (Fig. 2a). In the GCM-simulated nuclear war, the soot injection occurred on May 15 and within 10 days black carbon would spread out over most of the globe (Robock et al. 2007b). In China, the solar radiation drops immediately by about 30 W m^{-2} for all locations. The temperature also responds rapidly by decreasing by more than 1°C in that first summer and by about 2°C in the following summer. Average precipitation in China decreased around 0.3 mm/day for years 0 and 1, and for different locations, extreme floods and droughts occurred (Fig. 3). Since rice was planted on March 25 and during late May and June, it was at the panicle initialization stage, a regional nuclear war on May 15 would damage rice production in Mainland China right after the injection occurred. (A panicle is a branched cluster of flowers, and panicle initialization is a crucial part of the rice phenology.) Therefore, for year 0, rice production decreased 19 % comparing with the control run (Fig. 2a). In year 2, the average precipitation returned almost back to the level of control run; spring temperature was still 2°C less than control, while in summer, at some locations, temperature started to show a was still 10 W m^{-2} less than for the GCM control run (Fig. 3).

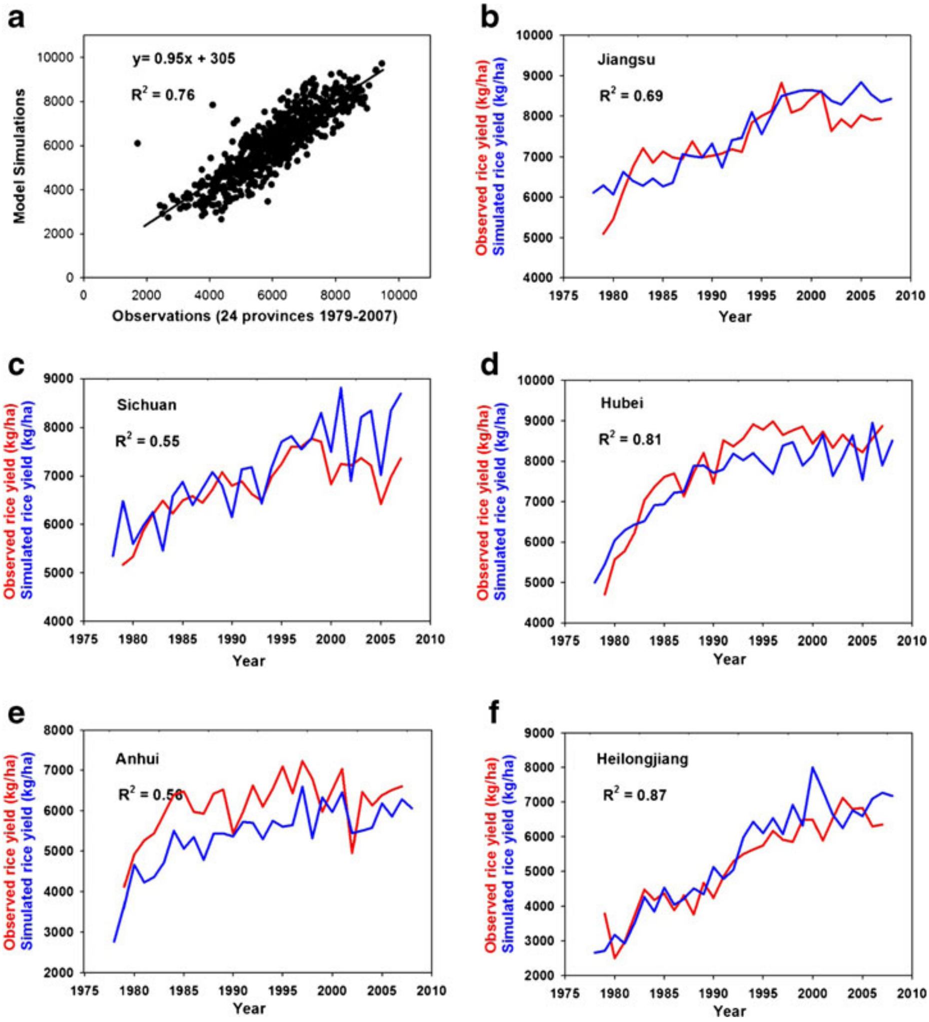

Fig. 1 (**a**) Comparison of DSSAT simulated rice yield and observations for the 24 provinces. R^2 is the coefficient of determination. Also shown are time series of simulated rice yield and observations for the top five rice production provinces: (**b**) Jiangsu, (**c**) Sichuan, (**d**) Hubei, (**e**) Anhui, and (**f**) Heilongjiang (1979–2007)

With those extreme climate changes in the first 3 years after injection (include the year injection occurred), without adaptation strategies, rice production in China (24 provinces) would be around 74 Mt, which is a reduction of 22 Mt compared to the control run. Chinese single cropping rice production in 2008 was 126 Mt, accounting for 65 % of the total rice production (Ministry of Agriculture of the People's Republic of China 2009). Since double cropping early rice is planted earlier than single cropping rice, and needs higher temperatures in the spring, and double cropping late rice needs more sunlight in the fall, a much colder spring and reduced solar radiation climate due to nuclear war would damage double cropping rice production as well. Also, due to regional climate change, regions planting double cropping rice may only be able to cultivate one single crop. In that case, total rice production would be reduced more than the 23 % we simulated within the first 3 years after a

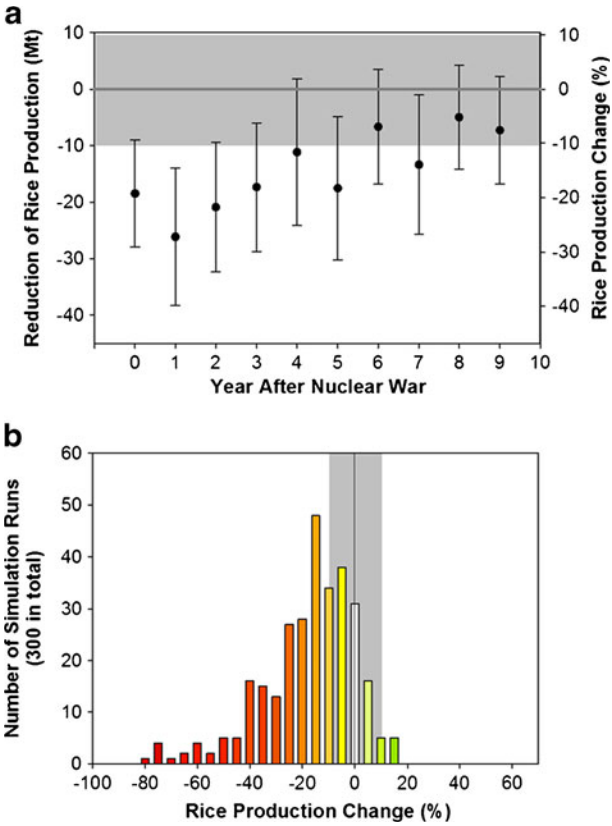

Fig. 2 Statistics of national rice production reduction after regional nuclear conflict. (**a**) Reduction of rice production with whiskers showing one standard deviation for each nuclear war year. (**b**) Distribution of rice production change (%): hot colors indicate negative changes and green shades indicate positive changes. The gray area in both panels shows ±1 standard deviation from the control runs, illustrating the effect of interannual weather variations

regional nuclear war. Rice production slowly recovered after year 1. For the last 2 years of our simulation (years 8 and 9), average rice production reduction is 6 %, which is within the natural variability of rice yield (Fig. 2a).

Figure 2b is the distribution of rice production change in China (%). Rice production change in China (%) is defined as:

$$\text{Rice production change in China } (\%) = \frac{\sum_{i=1}^{24} (Yield_{NW})_i \times (Rice\ planting\ area)_i - \sum_{i=1}^{24} (Yield_{CR})_i \times (Rice\ planting\ area)_i}{\sum_{i=1}^{24} (Yield_{CR})_i \times (Rice\ planting\ area)_i} \times 100\% \tag{1}$$

where i is province, $Yield_{NW}$ is rice yield affected by nuclear war, and $Yield_{CR}$ is rice yield in the control run. We assume that rice planting areas are the same as in 2008. Consistent with

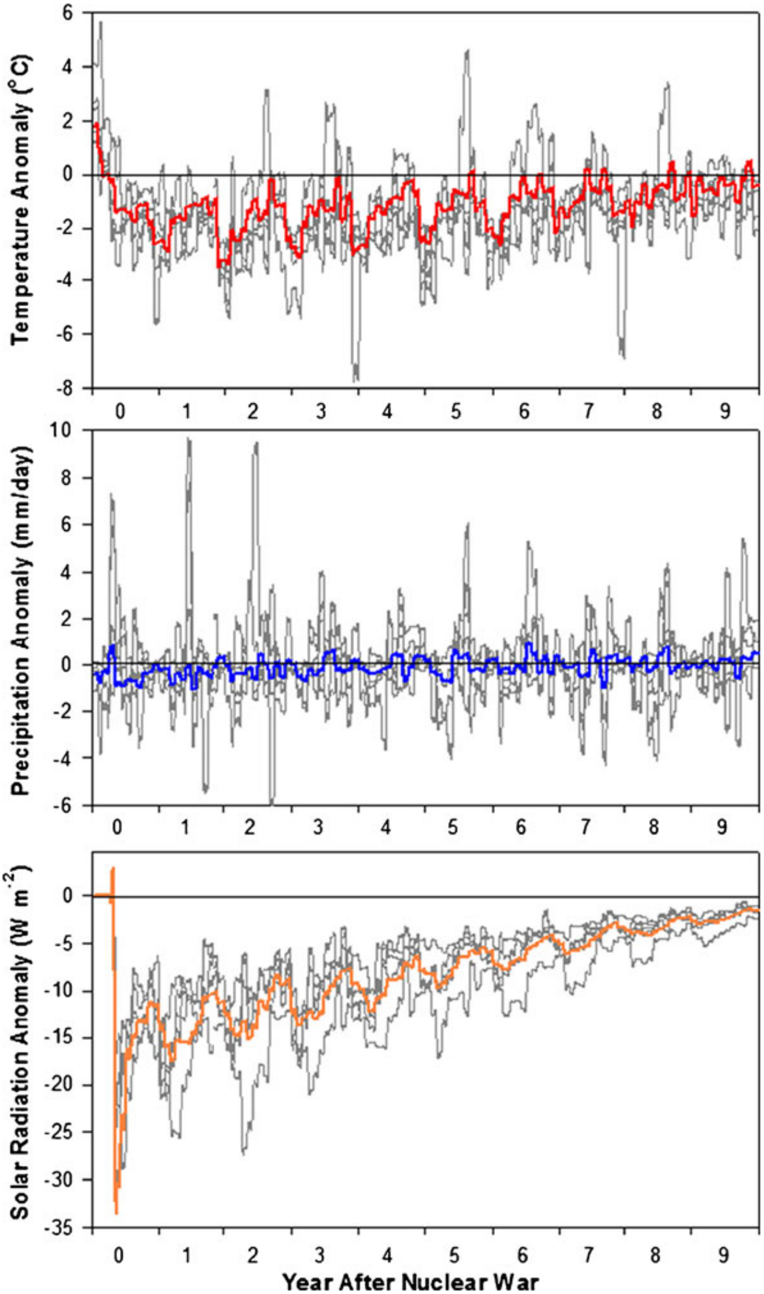

Fig. 3 Weather anomalies from a regional nuclear war with 5 Tg black carbon injection (Robock et al. 2007b). Gray lines are the weather anomalies for Sichuan, Jiangsu, Hubei, Anhui. and Heilongjiang. The red line is the average temperature anomaly for all 24 locations; the blue line is the average precipitation anomaly for all 24 locations; and the orange line is the average solar radiation anomaly for all 24 locations

the previous figures, rice production decreased in most of the runs. The peak of the distribution is from −7.5 % to −27.5 %, and 137 runs were within this range (Fig. 2b).

There were 55 runs showing rice production reduction larger than 30 %, referring to the first three nuclear war years when climate changes were severe. There were also 43 runs showing positive changes, but 35 runs were within the ±10 % natural variability. Therefore, 8 runs had significant positive response to a regional nuclear war. Those positive change regions are located in the south of China, where currently rice is under heat stress already, and temperature reduction due to nuclear conflict would increase rice yield there.

The above simulations were conducted for the past climate. However, if this regional nuclear conflict happened in the future, rice production in Mainland China would decrease as well. As the planet warms, the impacts will still be with respect to the current agricultural practices and have a cooling impact. Nevertheless, we have done additional simulations with temperature increasing 1°C and 2°C with no changes to the precipitation or solar radiation climate. Compared with simulations under the past climate, rice production in the first 3 years increased 6 Mt and 10 Mt, respectively, but was still 17 % and 13 % less than the control run respectively for the +1°C and +2°C cases (Fig. 4). Under an A1B scenario, in 2100 global average temperature would increase by around 2°C (IPCC 2007). Therefore, if a regional nuclear war occurred within this century, rice production in China would still decrease by at least 13 % at the first several years after this nuclear event, all other things being equal.

3.3 Different regional responses

As discussed above, different initial regional climates would lead to different responses of rice production perturbed by the same injection event. Figure 5 shows average rice yield reductions of 30 individual simulations at different locations in two different periods after a regional nuclear war event. Rice yield change (%) is defined as:

$$\text{Rice Yield Change } (\%) = 100\% \times \frac{Yield_{NW} - Yield_{CT}}{Yield_{CT}} \tag{2}$$

In the first period after nuclear war (years 0–3) (Fig. 5), rice grown in northern China is damaged dramatically. In Heilongjiang (9) and Neimenggu (17), rice growth almost completely failed, with average yield reduction close to 100 % (Figs. 5 and 6d); other provinces in the North all showed yield reduction around 50 %. The situations in provinces in the

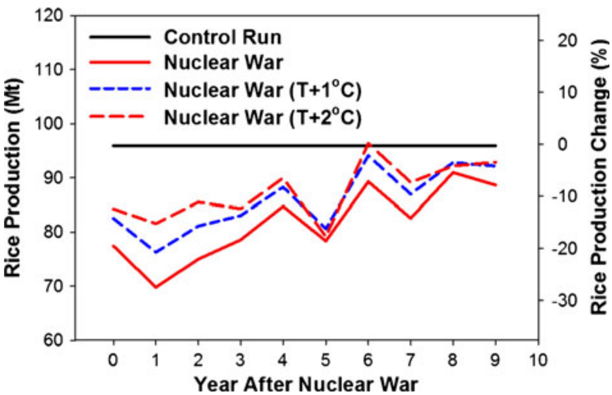

Fig. 4 Time series of rice production changes after increasing temperature by 1°C and 2°C. Red line is rice production under nuclear war impacts, and black line is control run. The blue dashed line is rice production after increasing temperature by 1°C. The red dashed line is rice production after increasing temperature by 2°C

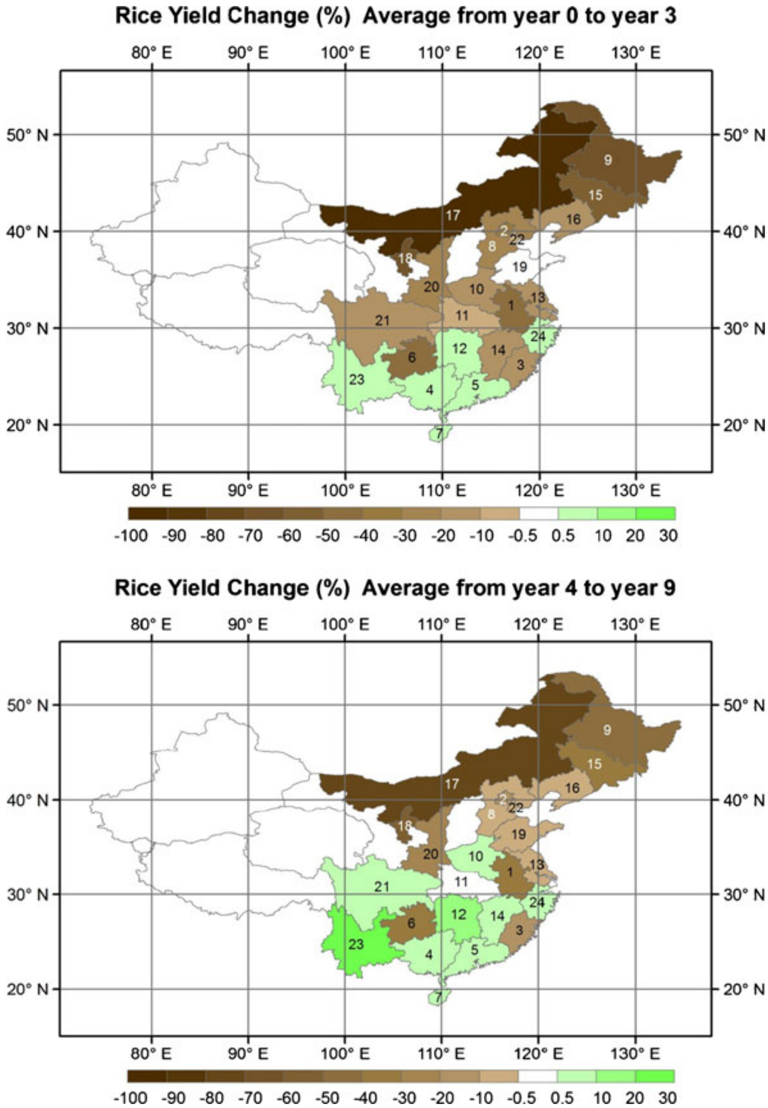

Fig. 5 Map of rice yield reduction (%) for two different periods after regional nuclear conflict. Brown indicates negative change, and green indicates positive change. The numbers correspond to the names of the different provinces listed in Table 1. White regions without numbers are provinces for which we did not conduct model simulations

central and southwestern China are not optimistic as well. Rice yield in Sichuan, the province with the largest rice production, decreased 13 % (Fig. 6c). Jiangsu (13), Hunbei (11), and Anhui (14), which are also major rice production regions in southern China, suffered from the small nuclear war with rice yield reductions of 10–42 % (Fig. 5). However, a few regions along the south and east coasts of China showed positive rice yield change (Figs. 5 and 6a and b). According to the average of 31 years of observations, Hainan, Guangdong, and Guangxi have higher temperature in spring (>15°C) and more precipitation

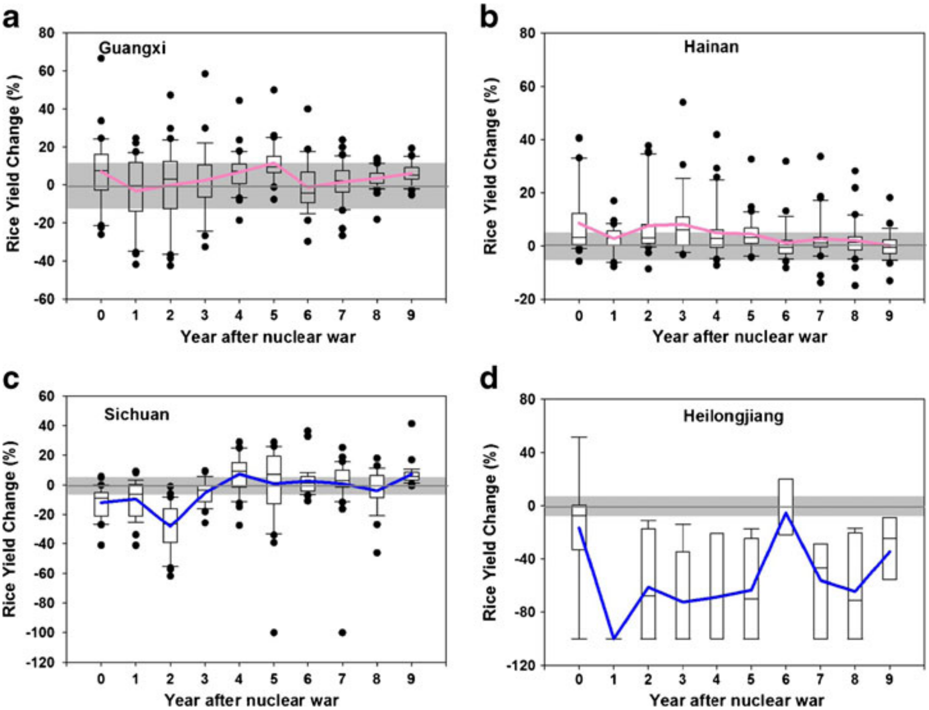

Fig. 6 Time series of rice yield reduction due to regional nuclear war in (**a**) Guangxi, (**b**) Hainan, (**c**) Sichuan and (**d**) Heilongjiang. Pink and blue lines are average of 30 individual simulations for each nuclear war year. Pink indicates positive change, and blue indicates negative change. The box plots indicate the statistical distribution of 30 runs for one nuclear war year: the horizontal lines from bottom to top are: 3 standard deviations below mean, lower quartile, median, upper quartile and 3 standard deviations above mean, and the black dots are outliers

in summer (>6 mm/day) than other regions. Therefore, the decrease of temperature due to nuclear war may not harm the rice emergence and juvenile stages.

In the second period after nuclear war (years 4 to 9), rice yield was still reduced in over half of China's provinces considered here, but was less extensive than during the first period (Fig. 5). Compared with the first several years, there were more regions in the South showing positive yield change.

3.4 Adaptation

Different regional responses of rice yields provide one possibility to adapt to the severe black carbon injection scenario. After black carbon injection, regions along the south and southeast coasts of China would be more favorable to rice growth, while northern and central China would not. Therefore, if cultivated land, agricultural techniques, and governance would be available, and if rice planting activity could be enhanced in the South, then the increase of rice production in those provinces following regional nuclear war might be able to compensate for the reduction of rice production in regions affected negatively.

The top provinces with negative changes (Ningxia (18), Neimenggu (17), Heilongjiang (9), and Jilin (15)) and positive changes (Guangdong (5), Guangxi (4), Hainan (7), Zhejiang (24) and Yunnan (23)) were selected to minimize rice production reductions by planting area changes. We investigated an increase of 40 % of rice planting area in those five southern provinces. However, Hainan does not have enough planting land to extend rice agricultural activity (Ministry of Agriculture of the People's Republic of China 2009). Therefore, only four provinces increased planting area. After increasing rice planting areas by 40 % in the four provinces with positive response, and reducing 40 % of rice planting areas in the four provinces with the highest negative response, rice production in China (24 provinces) increased 8–12 Mt under the nuclear war scenario (Fig. 7). In that case, regional nuclear war only would only affect the yield during the first 3 years after its occurrence. Starting from the third year, rice production would be back to the level of the control run.

However, in reality, moving rice planting zones is much more complicated. First of all, increasing rice planting areas in southern China must reduce planting areas for other crops. For example, Zhejiang is a dominant province for corn, winter wheat, and soybean. If we switch 22 % of total cultivated land in Zhejiang from other crops to rice, production of other crops would decrease, in addition to impacts from the nuclear war without even considering the possible impacts of climate changes on the yields of other crops. It would be very hard to balance our demands for different crops. Second, it is quite possible that climate change due to nuclear war would make southern provinces favorable for most of the major crops, and damage agricultural capability in the whole of northern China, where the corn belt is. If we depended on moving planting zones to adapt to nuclear war, we would not have enough cultivated land in southern and southeastern China for all of those agricultural activities. In addition, the south and southeast coast is the economic center of China. Switching their function from industry and financial centers to agricultural usage would be a huge challenge to the Chinese government.

Another way to adapt to the nuclear war scenario is changing agricultural practice. For example, we tested increasing fertilizer usage. In previous simulations with nuclear war impacts, a fixed fertilizer amount, 150 kg/ha, was used when planting, which is less than the average fertilizer used for the evaluation process (173 kg/ha). Therefore, we increased fertilizer applied to 200 kg/ha in all 24 provinces. With 200 kg/ha fertilizer, rice yields in

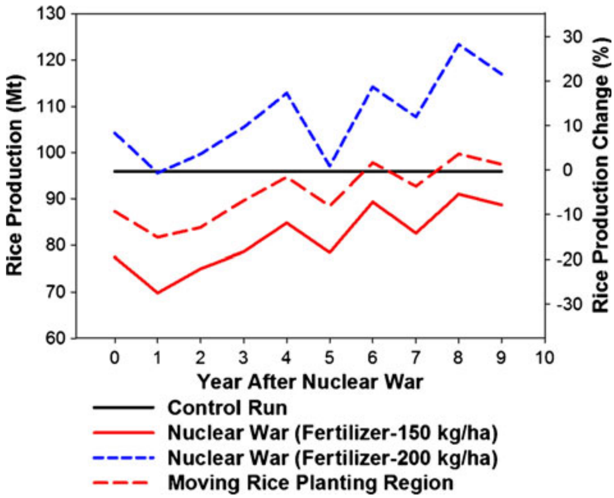

Fig. 7 Time series of rice production changes after moving rice planting area and after increasing fertilizer usage. Red line is rice production under nuclear war impacts, and black line is control run. Red dashed line is rice production after moving rice planting region to the South. The blue dashed line is rice production after increasing fertilizer applied from 150 kg/ha to 200 kg/ha

24 provinces increased by 5–30 %. In total, rice production in China (24 provinces) increased 18–32 Mt with the additional 50 kg/ha fertilizer (Fig. 7). In that case, increasing 50 kg/ha of fertilizer could totally compensate for these regional nuclear war impacts on rice production in China.

However, although fertilizer can greatly increase crop yield, it is not a panacea. Fertilizer induces several environmental problems. For example, fertilizer used in agriculture is a source of surface N_2O emission. From 1860 to 1990, global annual N_2O emission increased from 8 Tg to 11 Tg primarily because of increases in N usage in the food production system (Galloway et al. 2004). The increase of N_2O concentration in the atmosphere could cause ozone depletion in the stratosphere (Ravishankara et al. 2009) in addition to the strong ozone depletion due to black carbon (Mills et al. 2008). But N_2O is also a strong greenhouse gas (Crutzen et al. 2008), and warming due to N_2O could partially offset the cooling effect from a regional nuclear war. However, even if we assume that fertilizer usage all over the world would increase 50 %, N_2O emission would increase 10 % (Mosier et al. 1998). If we simply assume that N_2O concentration in the atmosphere also increases 10 %, then it would only increase global temperature by 0.1°C and could not significantly compensate for global cooling from a nuclear war event. Also, the ability of fertilizer to increase crop yield is not linearly related to the amount applied. We did some additional runs with 300 kg/ha fertilizer applied. The first additional 50 kg/ha fertilizer increased rice production by 18–32 Mt, and the next additional 100 kg/ha fertilizer only increased rice production by 10–17 Mt. Therefore, there is a limit to the effectiveness of fertilizer usage.

In summary, there is no simple solution to compensate for nuclear war impacts on production of rice or other crops. The best way to solve this problem is no nuclear war in the first place. Agriculture is vulnerable to climate change. Nuclear war, even a regional nuclear war, would change global climate significantly, and many important agricultural centers may be strongly affected. Although world food storage could temporarily solve some urgent problems, nuclear war impacts on agriculture could last for years, not just from the climate change aspect, but also from the consequences on the economy, societal structure, technology, and labor support.

3.5 Uncertainty

There are several uncertainties in this study: (1) GCM scenarios of climate change are likely to smooth over small scale spatial variability (Mearns et al. 2001). Since our simulations are location-based, the incompatible spatial resolution between the GCM used for the nuclear war simulation and the DSSAT crop model is one of the major uncertainties. (2) We only used climate change output from one climate model. This study should be repeated with other scenarios to examine this dependence. (3) Climate output from the nuclear war simulation is monthly averaged. This average could hide the intensity of daily precipitation, which is important for rice growth, especially in our simulations without the irrigation function turned on. Also, those monthly averaged temperature anomalies cannot reflect the change of the daily diurnal temperature change, which is important to rice. (4) Insufficient agriculture practice information could cause uncertainty. This study is only based on currently available agricultural practice information. More accurate input would provide more details but the dominant reduction trend should be the same. (5) Several factors affecting rice production after a nuclear war have not been considered in this study. For example, after a nuclear war, ultraviolet radiation at the surface would increase due to ozone depletion in the stratosphere (Mills et al. 2008), which would have a significant impact on crop yield.

4 Conclusions

A regional nuclear war between India and Pakistan with 5 Tg black carbon injection could decrease single cropping rice production by 23 % in Mainland China in the first 3 years after a nuclear event occurred. The annual rice production would return to the level of 1995, when the Chinese population was 133 million less than 2010. This impact could last for years with slow recovery. At the end of our simulation, rice production was still 6 % less than in the control run. Rice yields in different regions respond differently to this regional nuclear war because of different regional climate and different regional climate anomalies. For example, Heilongjiang is the most northerly province in China. During the 10 years after nuclear war, there was no rice production in most of the simulations. Sichuan is an inland province located in the southwest of China. Its rice production dropped 10–28 % in the first 3 years, and slowly recovered later. Hubei is in the center of China, and rice production there decreased 5 % at the beginning, and came back to the control run level after the third nuclear war year. Zhejiang and Hainan are on the east and south coast of China. Instead of negative impacts from nuclear war on single cropping rice production, their rice production increased by 8–11 % compared with control runs through all 10 years.

Those different responses provide one possibility to adapt to the severe black carbon injection event, that is moving the rice planting zone more to the south and east coasts. However, this is not a strategy we can depend on, although our simple calculation showed that it is possible to increase rice production to the level of the control run after the first 3 years damage, if we could increase 40 % of rice planting land in four provinces that are "benefitted" from this event and decrease 40 % of cultivated land for rice in another four provinces whose rice production is damaged by the negative impacts. Changing agriculture structure is a more complicated challenge than just changing the planting area. It would involve many other aspects, such as government regulation, the economic system, technology, and labor support. And it is the same argument for increasing fertilizer usage to adapt to such climate change. First of all, even if we do not consider other side effects, fertilizer cannot magically increase crop yield with no limit. There is a maximum fertilizer amount that can be effective under certain climate scenarios. And if there were a nuclear war between superpowers, global temperature would decrease 20–30°C (Robock et al. 2007a). In that case, even we applied kilotons of fertilizer per hectare, it would be impossible for agriculture to recover. Second, we have to investigate the side effects from the fertilizer, such as its impacts on the nitrogen cycle, ozone depletion in the stratosphere, and possible ozone generation in the lower troposphere. Without considering possible consequences, our "solution" would put us into a worse situation. Therefore, the best solution to deal with nuclear war impacts on agriculture is a nuclear-weapon-free world.

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