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Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000

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[1] Decreased methane emissions from paddy rice may have contributed to the decline in the rate of increase of global atmospheric methane (CH_4) concentration over the last 20 years. In China, midseason paddy drainage, which results in substantial reductions in growing season CH_4 fluxes, was first implemented in the early 1980s, and has gradually replaced continuous flooding in much of the paddy rice area. We constructed a regional prediction for China's rice paddy methane emissions using the DNDC biogeochemical model. Results of continuous flooding and midseason drainage water management simulations for all paddy rice fields in China were combined with regional scenarios for the timing of the transition from continuous flooding to predominantly midseason drainage to generate estimates of total methane flux for 1980, 1985, 1990, 1995, and 2000. The results indicate that CH_4 emissions from China's paddy fields were reduced over that period by about 40% (~5 Tg CH_4 yr^{-1}). *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1615 Global Change: Biogeochemical processes (4805); 9320 Information Related to Geographic Region: Asia. **Citation:** Li, C., J. Qiu, S. Frolking, X. Xiao, W. Salas, B. Moore III, S. Boles, Y. Huang, and R. Sass, Reduced methane emissions from largescale changes in water management of China's rice paddies during 1980–2000, *Geophys. Res. Lett.*, *29*(0), XXXX, doi:10.1029/2002GL015370, 2002.

1. Introduction

[2] The rate of growth of methane concentration in the atmosphere slowed from 10–15 ppb yr^{-1} in the 1980s to 0–5 ppb yr^{-1} for most years in the 1990s, though the annual increase in methane concentration was more variable during the 1990s than the 1980s [*Dlugokencky et al.*, 2001]. Large-scale temperature and precipitation anomalies have been identified as possible causes of the interannual variability in the rate of increase of methane concentration [e.g., *Hogan and Harriss*, 1994; *Dlugokencky et al.*, 2001], but these factors are not likely to explain the decadal trend to lower rates of growth of methane concentration (1990s vs. 1980s), which are likely to be due to a persistent change in methane source and/or sink strength or to an approach to steady state. Changes in the oxidation chemistry of the atmosphere could lead to an increase (or decrease) in the rate of methane oxidation (i.e., removal from the atmosphere), and thus to a decrease (or increase) in the atmospheric concentration growth rate [*Bekki et al.*, 1994; *Dlugokencky et al.*, 1996; *Karlsdottir and Isaksen*, 2000]. Decreased CH_4 emissions from the gas industry may have occurred in the early 1990s, particularly following the economic slowdown in the Soviet Union [*Dlugokencky et al.*, 1994; *Law and Nisbet*, 1996]. *Lowe et al.* [1997] analyzed the seasonal dynamics of both methane concentrations and their isotopic signatures and concluded that these changes were consistent with reductions in biomass burning as a CH_4 source during 1992. *Dlugokencky et al.* [1998] note that both methylchloroform data and changes in the seasonal peak-to-peak amplitude in methane concentration are consistent with a constant CH_4 lifetime (i.e., constant source and sink strengths or offsetting changes in both), and that the decline in the growth rate could be due to atmospheric methane approaching a new steady state. No consensus for the slowing of the atmospheric methane concentration growth rate has emerged yet [*Prather and Ehhalt*, 2001]. In this paper we propose an additional factor, diminishing methane emissions from rice paddies.

[3] Seasonally flooded rice paddies are a significant source of methane to the atmosphere, contributing ~40 Tg CH4 yr^{-1} [*Sass et al.*, 1999], or 8% of total global emissions. China has ~20% of the world's rice paddies [*FAOSTAT*, 2002]. Over the past two decades, midseason drainage as an alternative water management approach has been adopted throughout China [*Shen et al.*, 1998; *MWRUC*, 1996]. In contrast to traditional water management, which keeps paddy soils continuously flooded during the rice-growing season, with midseason drainage the rice fields are periodically drained or allowed to dry. In China, 2-5 drainings during a growing season is a common management practice (Qingmu Chen, Chinese Academy of Agricultural Sciences, personal communication). Midseason drainage or drying tends to increase rice yield by increasing N-mineralization in the soil and by increasing root development in the rice plants [*Wassmann et al.*, 2000; *Lu et al.*, 2000]. While the primary motivation for this draining has been to increase yields, a significant consequence has been to reduce methane emissions. Field studies have shown that midseason draining reduces total crop-season methane emissions by 10–80% [*Sass et al.*, 1992; *Yagi et al.*, 1996; *Sigren et al.*, 1997; *Cai et al.*, 1999; *Wassmann et al.*, 2000]. We combined a process biogeochemistry model with spatial datasets of soil properties,

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paddy distribution, crop rotations, daily weather, and additional agricultural management factors to simulate annual methane emissions from China's rice paddies under scenarios of continuous flooding and mid-season draining.

2. Methods

[4] Because there are no reliable, detailed historical data sets on the spatial and temporal distribution of paddy fields or rice cultivar use, it was not possible to conduct a fully realistic 20-year simulation for China. Instead, we have adopted 1990 as a mean representative year, and simulated two water management scenarios, continuous flooding and 3 mid-season drainings. We then constructed a scenario at the provincial scale of the transition in water management from continuous flooding to mid-season draining, 1980–2000, and estimated CH4 emissions for 1980, 1985, 1990, 1995, and 2000 by averaging emissions by province for the two water management scenarios, weighted by estimated paddy area managed under each scenario.

2.1. Biogeochemical Model

[5] The DNDC (DeNitrification-DeComposition) biogeochemical model was developed for predicting carbon sequestration and trace gas emissions for non-flooded agricultural lands. [*Li et al.*, 1992; 1994; 1996]. Under extended submerged conditions, paddy soils have almost constant moisture content and oxygen's role in the oxidation-reduction processes is significantly diminished. To predict soil Eh dynamics under both aerated and submerged conditions, a simple kinetic scheme was developed for DNDC to capture the soil redox dynamics [*Li et al.*, 2000]. Combining the Nernst equation and the Michaelis-Menten equation, DNDC simulates the interactions among substrates, soil Eh, and the activity of microbial reducers. Each soil layer is divided into two zones, aerobic and anaerobic, based on simulated soil Eh values. When the anaerobic fractional volume increases, more substrates are involved in reductive reactions (e.g., methanogenesis); when the anaerobic fractional volume shrinks, more substrates are involved in oxidative reactions (e.g., methanotrophy). With a dynamic anaerobic fractional volume, DNDC can simultaneously predict a series of oxidation-reduction processes in both wetland and upland soils [*Li*, 2000; *Li et al.*, 2000]. A detailed rice growth sub-model was also developed for DNDC [*Zhang et al.*, 2002] to quantify three dynamic parameters crucial for modeling CH$_4$ production and oxidation: total rice biomass, root development and biomass, and rice aerenchyma development. This new model has been tested against several methane flux data sets from wetland rice sites in the U.S., Italy, China, Thailand, the Philippines, and Japan; and was generally consistent with observations, with reduced emissions for mid-season drainage (Figures 1b, 1d, and 1f) compared to continuous flooding (Figures 1a, 1c, 1e, and 1g).

2.2. Spatial Datasets

[6] Meteorological data, soil properties, agricultural census data including crop areas, fertilizer use and other management data were obtained from ground-based statistical sources. Much of the statistical data was county-based, the county was chosen as the basic, spatial unit for our GIS database construction. Since each county is regarded to be uniform during the model simulation runs, uncertainty estimates related to the inherent heterogeneities of many input parameters within the county must be generated during the scaling-up process.

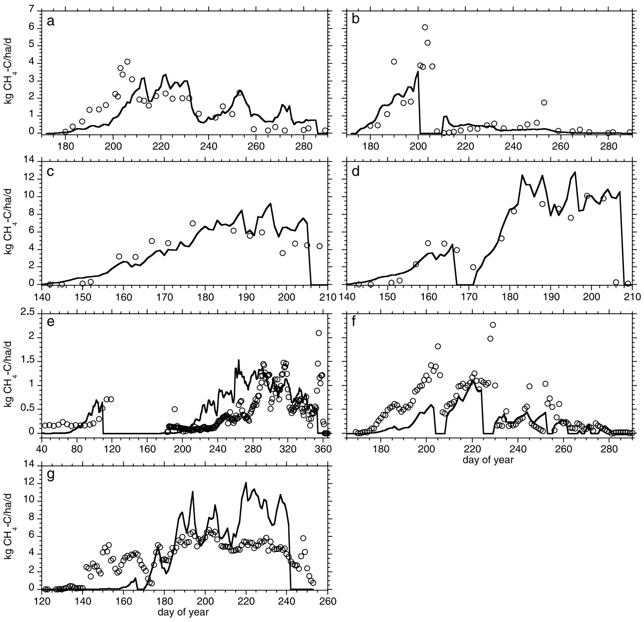

Figure 1. Measured (O) and simulated (lines) CH4 fluxes at 7 paddy rice field plots. Single rice with (a) continuous flooding midseason drainage and (b) midseason drainage at Jianning, Jiangsu Province, China [*Huang et al.*, 2001]; single rice with (c) continuous flooding and (d) midseason drainage at Beaumont, Texas, USA [*Sigren et al.*, 1997; R. Sass, unpublished data]; (e) double rice with continuous flooding at Prachin Buri, Thailand (unpublished field data, Jariya Boonjawat, Chulalongkorn Univ., Thailand); (f) single rice with midseason drainage at Wuxian, Jiangsu Province, China [*Zheng et al.*, 1999]; and (g) single rice with continuous flooding at Ver, Italy [*Butterbach et al.*, 1997]. Note changes in axes scales.

2.3. Paddy Field Crop Rotations

[7] By combining a county statistical database on crop sown areas with a Landsat TM derived land-cover map for all of mainland China, *Frolking et al.* [2002] estimated areas in each of 48 single and multiple crop rotations, including single rice and 10 different multi-crop paddy rice rotations.

2.4. Fertilizer and Manure

[8] Manure production was based on animal and human populations from the county database assembled by the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, using standard manure production rates [*IPCC*, 1997], and field application rates of 50% for animal manure and 10% for human manure.

2.5. Soils

[9] Maximum and minimum values of soil texture, pH, bulk density, and organic carbon content were derived for each county from digitization of national soil maps [*Institute*

Table 1. Paddy Areas (10^3 km^2), Fraction Drained, and Methane Flux (Tg CH_4 yr^{-1}) by Region in China

	Crop area[b]		Fraction drained					Methane flux[c] (Tg CH_4 yr^{-1})				
Region[a]	R-1	R-2	1980	1985	1990	1995	2000	1980	1985	1990	1995	2000
North	10	0.8	0.04	0.3	0.6	0.8	0.8	0.46	0.42	0.37	0.35	0.35
Northeast	26	0	0.05	0.3	0.6	0.8	0.8	0.68	0.62	0.57	0.54	0.54
Central	41	98	0	0	0.3	0.6	0.8	6.54	6.54	5.68	4.82	4.25
South	6	40	0	0	0.2	0.4	0.8	1.99	1.99	1.72	1.45	0.98
Southwest	40	24	0	0	0.3	0.6	0.8	2.41	2.41	2.00	1.59	1.32
Northwest	6	0.1	0	0.3	0.6	0.8	0.8	0.21	0.19	0.16	0.14	0.14
TOTAL	130	163	0.01	0.05	0.33	0.6	0.8	12.3	12.2	10.5	8.9	7.6

[a] *North*: Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan Provinces; *Northeast*: Liaoning, Jilin, and Heilongjiang Provinces; *Central*: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, and Hunan Provinces; *South*: Fujian, Guangdong, Guangxi, and Hainan Provinces; *Southwest*: Sichuan, Guizhou, and Yunnan Provinces; *Northwest*: Inner Mongolia, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang Provinces.

[b] R-1: single rice and rice plus non-rice double crop rotation; R-2: double rice and double rice plus non-rice triple crop rotation [*Frolking et al.*, 2002]. Areas in 10^3 km^2.

[c] Regional methane flux values (Tg CH_4 yr^{-1}) are the mean of the high and low emission estimates. Typical provincial flux ranges were ±10–35% of the mean for the continuous flooded scenarios and ±35–75% of the mean for the mid-season drained scenarios. The full range is reported for the national total Table 2.

of Soil Science, 1986] and other information [*National Soil Survey Office of China*, 1993–1997]. Model simulations could then be conducted for each county by choosing soil parameter values from within the observed range.

2.6. Management

[10] General data on tillage, planting and harvest dates, crop residue management, and crop varieties were taken from *CRTSA* [1995], *Huang et al.* [1997a], *Cui et al.* [1994], *Liu and Mu* [1993], and *Beijing Agricultural University* [1992]. *Shen* [1998] reported that, based on national statistics, an average of 30% of total crop residue (leaves + stems + roots) was returned to the soil, which we adopted for all fields.

2.7. Weather

[11] Daily weather for 1990 from 610 weather stations across China were acquired from the National Center for Atmospheric Research (http://dss.ucar.edu/index.html). Station data were assigned to each county on a nearest neighbor basis. Earlier simulations with only 175 stations yielded very similar results, and we are confident that the uncertainty in our results due to lack of climatic interpolation is small.

2.8. Water Management

[12] Detailed data on water management at the county scale were not available, so we developed a simple scenario of the evolution of paddy water management in China from 1980–2000, based on a recent Chinese publication and discussion with a member of the Chinese Academy of Agricultural Sciences. In the early 1980s, midseason drying was first successfully tested as a water conservation measure in northern China [*Shen et al.*, 1998]. Due to water savings and increased yield, the new management regime was widely adopted in northern China in the 1980s. In the 1990s, the technique was introduced to the major rice-producing areas along the Yangtze River. In the late 1990s, midseason drainage became popular in the southern provinces [*Shen et al.*, 1998]. The current (year 2000) fraction of rice paddies with alternative water management is ∼80% (Qingmu Chen, personal communication). We chose approximate values for the percent of paddies with mid-season drainage for six regions in China for 1980, 1985, 1990, 1995, and 2000 (Table 1). This is a very rough estimate, with an aim of characterizing the magnitude of change.

3. Results and Discussion

[13] Sensitivity tests conducted for typical rice fields in China indicated that CH_4 fluxes were most sensitive to soil texture values. Varying soil texture from its coarsest to its finest texture value reported in the county-scale database produced a range of CH_4 fluxes that was broad enough to cover more than 80% of the CH_4 variations caused by varying any or all other input parameters between minimum and maximum values. DNDC was run twice for each of the 11 rice crop rotation that occurred in each county, once with the maximum and once with the minimum soil texture value for the county. The final CH_4 fluxes are then expressed as ranges. The true CH_4 flux has a high probability of falling within the reported range. While this cannot be fully evaluated because of very limited field data, for five sites we compared our annual county-level emission range (not the site-specific simulations shown in Figures 1a, 1b, 1c, 1d, and 1f) to the reported emissions. For the two sites in China, the three scenarios of observed annual emissions were within the simulated range, while for the Texas site, the observed continuous flooding annual emission was below the simulated range and the observed mid-season drainage annual emission was above the simulated range.

[14] The predicted 1990 CH_4 emission ranges from all paddy rice fields in China were 2.3–10.5 Tg CH_4 yr^{-1} for the midseason drainage scenario and 8.6–16.0 Tg CH_4 yr^{-1} for the continuous flooding scenario. Changes in water management from continuous flooding to midseason drainage reduced both the high and low estimates by a similar amount, so we conclude that the change in national emissions due to changing water management is not very sensitive to soil texture variability. Water management scenario area-weighted averages were estimated for each province every five years from 1980 through 2000 (Table 1). From 1980 to 2000 China's annual rice paddy methane flux dropped from 8.6–16.0 Tg CH_4 yr^{-1} to 3.5–11.6 Tg CH_4 yr^{-1} (Figure 2).

[15] China produces ∼33% of the world's rice on ∼20% of the world's paddy land [*FAOSTAT*, 2002]. Multiplying the DNDC estimate of methane emissions for China's

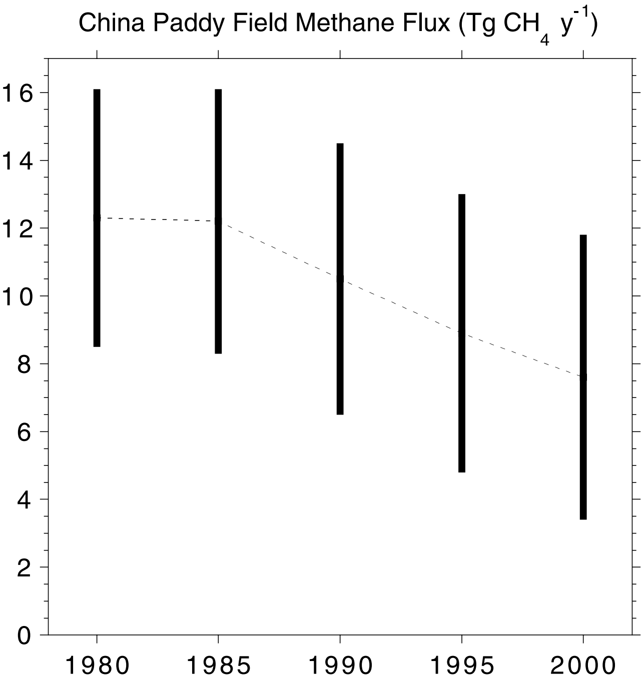

Figure 2. Total methane flux range for mainland China's rice paddies, as simulated by DNDC. Each vertical bar represents a likely range in emissions, based on simulations for the range in soil texture (coarse to fine) for each county in China (see text for details). The dashed line connects the mean values for each year. The simulated decline in emissions (~5 Tg CH_4 yr^{-1}) is due solely to changes in water management from continuous flooding to mid-season draining. All other factors were held constant.

paddies, continuously flooded, by 3 (production) to 5 (area) gives a global rice paddy methane flux estimate of 25–80 Tg CH_4 yr^{-1}, compared with recent global estimates of ~40 Tg CH_4 yr^{-1} [e.g., *Sass et al.*, 1999; *Neue and Sass*, 1998].

[16] The integrated reduction in CH_4 emissions from China's rice paddies from 1980 to 2000 is about 40 Tg (Figure 2). To quantify the impact this changing source strength would have on the atmosphere, we constructed a simple, one-box, first order model of atmospheric methane burden, with a constant global source of 595.7 Tg CH_4/yr, a methane lifetime of 8.4 years, and 1ppbv per 2.78 Tg CH_4 [*Prather et al.*, 2001], which had a steady state concentration of 1800 ppbv. If, over 20 years, the source strength drops by 4.7 Tg/yr (Figure 1 and Table 1, and assuming nothing else changes), the atmospheric concentration drops to 1792 ppbv. If the source continues at this lower rate (591 Tg CH_4/yr) the atmosphere reaches a new steady state of 1786 ppbv, after an additional 20 years. We conclude that reduced emissions from China's rice paddies probably played an important role in the reduced growth rate in the 1990s, but probably did not account for the majority of the change.

[17] Several additional factors could have influenced methane emissions from China's rice paddies from 1980 to 2000. First, weather patterns inevitably vary from one year to the next, but are not likely to have caused a two-decade-long trend in paddy methane emissions, particularly because paddies have managed water regimes. Second, nitrogen fertilizer use in China doubled from 1980 to 1999 [*FAOSTAT*, 2002]. Impacts of nitrogen fertilizer use on methane emissions from rice paddies are indirect and fertilizer_type dependent, and thus highly variable. Increased fertilizer use could lead to an increase in emissions due to an increase in rice plant productivity and biomass, or to a decrease due to soil Eh elevation induced by fertilizers such as ammonium sulfate [*Dunfield et al.*, 1995; *Schütz et al.*, 1989; *Lindau et al.*, 1990; *Denier van der Gon and Neue*, 1994; *Wassmann et al.*, 1994; *Yao and Chen 1994*). Third, the direct effects of rice cultivar type on methane emissions are complex, due to differences in aerenchyma development, biomass allocation to roots and grain, and total plant height and biomass [*Sass et al.*, 1990; *Kludze et al.*, 1993; *Denier van der Gon and Neue 1995*; *Huang et al.*, 1997b; *Ding et al.*, 1999], and no clear consensus has emerged from field measurements to date. New cultivars introduced in China between 1980 and 2000 generally have had lower stature and more allocation to grain [*Zhou et al.*, 2001]. New cultivars and increased fertilizer use raised China's overall mean rice yield by ~50% (Table 2). Finally, the area of rice paddies in China was fairly constant during the 1980s but declined by ~10% during the 1990s (Table 2; [*Seto et al.*, 2000]), likely with a similar decline in methane emissions. While all of these effects cannot be quantified with the biogeochemical model because of inadequate datasets to create complete scenarios, we estimate that their net effect will not have caused a significant, persistent change in methane emissions.

4. Conclusions

[18] Demand for rice in Asia is projected to increase by 70% over the next 30 years [*IRRI*, 2002; *Hossain*, 1997]. At the same time, population increase and intensification of economic development will lead to significant land use conversion [e.g., *Seto et al.*, 2000]. Paddy rice cropland distributions and management intensity (fertilizer use, cultivars, water management, multi-cropping) will have to change over the coming decades. As water resources become scarcer [*Vörösmarty et al.*, 2000], rapidly expanding urban/industrial areas will compete with agriculture for available water. In Asia, agriculture currently accounts for 86% of total annual water withdrawal [*IRRI*, 2002]. Urban demand for water will generally have greater financial and political leverage than agricultural demand for water, and for some regions water availability to agriculture may decline significantly over the next few decades. Rising water costs will force all agriculture to improve its water-use efficiency. As this occurs, the practice of midseason draining of rice paddies, which requires less water than

Table 2. Rice Paddy Statistics for China

Year	Area[a] (10^6 km^{-2})	Yield[a] (10^3 kg ha^{-1})	Production[a] (10^9 kg yr^{-1})	CH_4 flux (Tg CH_4 yr^{-1})
1980	0.34	4.1	143	8.6–16.0
1985	0.33	5.2	171	8.4–16.0
1990	0.34	5.7	192	6.6–14.4
1995	0.31	6.0	187	4.9–12.9
2000	0.30	6.3	190	3.5–11.6

[a] *FAOSTAT* [2002].

continual flooding, is likely to increase throughout many parts of Asia. Continuing changes in the rice paddy contribution to the global methane budget are likely over the coming decades.

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