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Modeling methane emission from rice paddies with various agricultural practices

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[1] Several models have been developed over the past decade to estimate CH_4 emission from rice paddies. However, few models have been validated against field measurements with various parameters of soil, climate and agricultural practice. Thus reliability of the model's performance remains questionable particularly when extrapolating the model from site microscale to regional scale. In this paper, modification to the original model focuses on the effect of water regime on CH_4 production/emission and the CH_4 transport via bubbles. The modified model, named as CH4MOD, was then validated against a total of 94 field observations. These observations covered main rice cultivation regions from northern (Beijing, 40°30′N, 116°25′E) to southern China (Guangzhou, 23°08′N, 113°20′E), and from eastern (Hangzhou, 30°19′N, 120°12′E) to southwestern (Tuzu, 29°40′N, 103°50′E) China. Both single rice and double rice cultivations are distributed in these regions with different irrigation patterns and various types of organic matter incorporation. The observed seasonal amount of CH_4 emission ranged from 3.1 to 761.7 kg C ha^{-1} with an average of 199.4 ± 187.3 kg C ha^{-1}. In consonance with the observations, model simulations resulted in an average value of 224.6 ± 187.0 kg C ha^{-1}, ranging from 13.9 to 824.3 kg C ha^{-1}. Comparison between the computed and the observed seasonal CH_4 emission yielded a correlation coefficient r^2 of 0.84 with a slope of 0.92 and an intercept of 41.1 ($n = 94$, $p < 0.001$). It was concluded that the CH4MOD can reasonably simulate CH_4 emissions from irrigated rice fields with a minimal number of inputs and parameters. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1620 Global Change: Climate dynamics (3309); 1615 Global Change: Biogeochemical processes (4805); 3210 Mathematical Geophysics: Modeling; *KEYWORDS:* model, CH_4 emissions, rice fields

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1. Introduction

[2] Methane is one of the principal greenhouse gases. *Rodhe* [1990] reported that CH_4 has about 15–30 times greater infrared absorbing capability than CO_2 on a mass basis and may account for 15–20% of the radiative forcing added to the atmosphere [*Houghton et al.*, 1996]. Worldwide, rice fields are thought to contribute 9–30% to global CH_4 emissions [*Matthews et al.*, 1991; *Sass*, 1995; *Houghton et al.*, 1996]. Projections based on population growth rates in countries where rice is the main food crop indicate that rice production must increase 65% by 2020 to meet the rice demand for the growing population [*International Rice Research Institute*, 1989]. This increase rice production will most likely be accompanied by an increase in methane emissions [*Bouwman*, 1991].

[3] Precise estimates of CH_4 emissions from rice fields have been difficult to determine due to large regional differences in spatial and temporal variability in climate, soils and agricultural practices. In earlier efforts, estimates were made by extrapolating field measurements to a regional or global scale [*Cicerone and Shetter*, 1981; *Holzapfel-Pschorn and Seiler*, 1986; *Schütz et al.*, 1989b], or by using a statistic relationship between methane emission and a certain variable such as the rice net primary production [*Aselmann and Crutzen*, 1989; *Taylor et al.*, 1991; *Bachelet et al.*, 1995], the rice grain production

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[*Anastasi et al.*, 1992] and the organic matter input [*Kern et al.*, 1995]. Nevertheless, large uncertainties might be introduced due to different regional factors in methane production, oxidation and emission processes. Thus models have become more and more important in estimating regional and global methane emissions [*Intergovernmental Panel on Climate Change* (*IPCC*), 2000].

[4] To obtain estimates of methane emissions from regional or global rice paddies via model method, it is essential to extrapolate the model from specific sites to a wider area by up scaling. Reliability of up scaling and thus the accuracy of the estimates mainly relies on two aspects, availability of a reliable input database and validity of CH_4 models. It is most important for modelers to validate their models to insure that observed results can be realistically described under various soils, climates and agricultural practices. Several models have been developed over the last decade to estimate CH_4 emission from rice paddies [*Cao et al.*, 1995; *Nouchi et al.*, 1997; *Arah and Stephen*, 1998; *Huang et al.*, 1998; *Li et al.*, 1994; *Li*, 2000; *Matthews et al.*, 2000; *Bodegom et al.*, 2001]. However, few models have been validated against field measurements with various parameters of soil, climate and agricultural practice because sufficient observations associated with these parameters were not available. Fortunately, since 1988 scientists have reported field observations of CH_4 emission from Chinese rice paddies under a variety of soils, climates and agricultural practices [e.g., *Shangguan et al.*, 1993; *Wang et al.*, 1994; *Wang*, 1996; *Khalil et al.*, 1998; *Cai*, 1999; *Cai et al.*, 2000; *Huang et al.*, 2001]. These studies offer a great opportunity to validate present models for the purpose of up scaling.

[5] With an understanding of the processes of methane production, oxidation and emission, *Huang et al.* [1998] developed a model to predict methane emission from rice paddy soils. The model associated these processes with rice growth, organic C depletion and environmental factors. Validated against independent field measurements of CH_4 emission from rice paddy soils in Texas of USA, Tuzu of China and Vercelli of Italy, Huang's model provides a realistic estimate of the observed results. (Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories [*IPCC*, 2000]).

[6] It has been recognized that water management such as periodic drainage and intermittent irrigation during rice growing period significantly reduces CH_4 emissions [*Yagi et al.*, 1996; *Mishra et al.*, 1997; *Yang and Chang*, 2001]. Decomposition of incorporated organic materials is the predominant source of methanogenic substrates in very early stages of rice growing [*Watanabe and Roger*, 1985] and the CH_4 emission via ebullition during this period contributed significantly to the total emissions [*Shangguan and Wang*, 1993]. However, Huang's model was primarily developed for continuous flooding and not for intermittent irrigation rice paddies. Moreover, the CH_4 emission via ebullition was not taken into account in their model. All of these factors may lead to significant errors if the model is employed to estimate CH_4 emission from rice paddies with various agricultural practices including water regimes and organic matter amendments.

[7] In this paper, we pay specific attention to the effect of water regime on CH_4 production/emission and the CH_4 transport via bubbles for modifying the CH_4 emission model developed by *Huang et al.* [1998]. The main objective of this paper is to realistically model field observations under various agricultural practices. A further objective is to focus on the estimates of CH_4 emission from regional or global rice paddy soils by linking the modified model with available databases of soil, climate and agricultural practice.

2. Model Description and Modification

2.1. Description of the Original Model

[8] We accept the hypothesis from the original model [*Huang et al.*, 1998] that methanogenic substrates are primarily derived from rice plants and added organic matter. Rates of methane production in flooded rice soils are determined by the availability of methanogenic substrates and the influence of environmental factors. Rice growth and development control the fraction of CH_4 emitted through plant.

2.1.1. Substrates From Organic Matter Decomposition

[9] Decomposition of organic matter in soil was simulated with a first-order kinetics equation [*Huang et al.*, 1998] as:

$$C_{OM} = 0.65 \times SI \times TI \times (k_1 \times OM_N + k_2 \times OM_S) \qquad (1)$$

where C_{OM} is the daily amount of carbohydrate degraded from organic matter amendments (g m^{-2} d^{-1}). The impact of soil texture and soil temperature on decomposition was quantified by the soil index (*SI*) and the temperature index (*TI*), respectively. OM_N and OM_S represent nonstructural and structural components of incorporated organic matter (g m^{-2}, dry matter), respectively. Constants k_1 and k_2 represent the first-order potential decay rate for OM_N and OM_S with the values of 2.7×10^{-2} and 2×10^{-3} d^{-1}, respectively [*Huang et al.*, 1998]. The constant 0.65 is a reduction factor of field flooding on decomposition [*Huang et al.*, 2002].

2.1.2. Substrates Associated With Rice Plants

[10] The amount of carbohydrates derived from rice plants was simulated by the following equation [*Huang et al.*, 1998]:

$$C_R = 1.8 \times 10^{-3} \times VI \times SI \times W^{1.25} \qquad (2)$$

where C_R represents carbohydrate (g m^{-2} d^{-1}) derived from rice plants and W is rice aboveground biomass (g m^{-2}) on a given day. *VI* is a variety index identifying relative difference in methane production among rice varieties. Rice aboveground biomass was computed by a logistic growth equation [*Huang et al.*, 1998] as:

$$W = \frac{W_{\max}}{1 + B_0 \times \exp(-r \times t)} \qquad (3)$$

$$B_0 = W_{\max}/W_0 - 1 \qquad (4)$$

$$W_{\max} = 9.46 \times GY^{0.76} \qquad (5)$$

where W_0 and $W_{\max}$ represent rice above ground biomass at transplanting and at harvesting, respectively. Time variable t (d) is scaled in days after transplanting. The *GY* is rice grain yield (g m^{-2}). The constant r is an intrinsic growth rate for above ground biomass.

2.1.3. Influence of Environmental Factors

[11] The effect of soil texture on CH_4 production was expressed by a dimensionless soil index (SI) that is linked with soil sand content ($SAND$) as equation (6) [*Huang et al.*, 1998]. The TI was introduced to quantify the influence of soil temperature on CH_4 production as equation (7) [*Huang et al.*, 1998].

$$SI = 0.325 + 0.0225 \times SAND \tag{6}$$

$$TI = Q_{10}^{\frac{T_{Soil}-30}{10}} \quad (\mathrm{T_{soil}} = 30 \text{ for } 30 < \mathrm{T_{soil}} \leq 40^\circ\mathrm{C}) \tag{7}$$

[12] Q_{10} is a temperature coefficient for a process involved in biochemical and microbial activities. Field measurements suggested that the Q_{10} for methane emission ranged from 2 [*Khalil et al.*, 1991] to 4 [*Schütz et al.*, 1989a]. A Q_{10} value of 3.0 was assumed [*Huang et al.*, 1998].

[13] The effect of soil redox potential (Eh) on methane production was described by equation (8).

$$F_{Eh} = \exp\left(-1.7 \times \frac{150 + Eh}{150}\right)(\mathrm{Eh} = -150 \text{ for Eh} < -150 \text{ mv}) \tag{8}$$

where F_{Eh} is a reduction factor of soil redox potential, $0 < F_{Eh} \leq 1.0$ [*Huang et al.*, 1998].

2.1.4. Dependence of Methane Production on Substrates and Environment

[14] The net reaction of anaerobic carbohydrate fermentation with methanogenesis was assumed to be an overall reaction of $C_6H_{12}O_6 \Rightarrow 3CH_4 + 3CO_2$. From this reaction, a conversion factor on a mole weight basis of $C_6H_{12}O_6$ to CH_4 is approximately 0.27 ($3[CH_4]/[C_6H_{12}O_6] = 0.27$). Rate of methane production, P (g m^{-2} d^{-1}), is then determined by the availability of methanogenic substrates and the influence of environmental factors by the equation:

$$P = 0.27 \times F_{Eh} \times SI \times TI \times \left[\left(1.8 \times 10^{-3} \times VI \times W^{1.25}\right) + 0.65 \times (k_1 \times OM_N + k_2 \times OM_S)\right] \tag{9}$$

2.1.5. Methane Emission Via Rice Plants

[15] The fraction of produced methane emitted via rice plants, F_p, was simulated by [*Huang et al.*, 1998]:

$$F_p = 0.55 \times \left(1 - \frac{W}{W_{\max}}\right)^{0.25} \tag{10}$$

where W and $W_{\max}$ has the same definition as in equation (3).

[16] The CH_4 emission via plants (E_p) was then computed as:

$$E_p = F_p \times P \tag{11}$$

2.2. Modifications to the Original Model

2.2.1. Methane Emission Via Bubbles

[17] Methane emitted via bubbles was observed in flooded rice paddies [*Schütz et al.*, 1989a; *Nouchi*, 1994; *Denier van der Gon and Neue*, 1995; *Wassmann et al.*, 1996]. When the flooded soil reaches the max solubility of CH_4, produced methane in the soil will aggregate to form bubbles, travel straight upward to the water surface, and finally release into the atmosphere with very little oxidization. The methane ebullition occurs predominantly in the early phase of rice growth season, and trails off as the rice matures [*Shangguan et al.*, 1993]. We simply adopted the equation by *Li* [1999] to simulate this process.

$$E_{bl} = 0.7 \times (P - P_0) \times \ln(T_{\mathrm{soil}})/W_{\mathrm{root}} \tag{12}$$

where E_{bl} represents the CH_4 emission rate (g m^{-2} d^{-1}) via bubbles. P is CH_4 production rate (g m^{-2} d^{-1}). P_0 is a criterion when the bubbles occur and was quantified as 0.002 (g m^{-2} d^{-1}) [*Li*, 1999]. T_{soil} is the soil temperature (°C). W_{root} is the rice root biomass (g m^{-2}) that is described by the above ground biomass (W) as [*Yoshida*, 1981]:

$$W_{\mathrm{root}} = 0.136 \times (W_{\mathrm{root}} + W)^{0.936} \tag{13}$$

For a given aboveground biomass of W, we set $W_{\mathrm{root}}^{(0)} = 0$ to start the iteration and set $W_{\mathrm{root}}^{(\mathrm{i}+1)} - W_{\mathrm{root}}^{(\mathrm{i})} < 0.1$ as a limiting criterion.

2.2.2. Effect of Water Managements on Soil Eh

[18] *Mishra et al.* [1997] studied the effect of water regimes (continuously flooded, continuously nonflooded, alternately flooded) on CH_4 flux from rice-planted soil. They found that the Eh was always high under nonflooded conditions, but dropped rapidly within several days after flooding. In intermittently flooded regimes, the Eh increased with a shift from flooded to nonflooded conditions [*Mishra et al.*, 1997]. The original model simulated changes in soil Eh for the conditions from nonflooded to flooded but did not for the intermittently flooded regimes [*Huang et al.*, 1998]. The change in soil Eh is also associated with soil type and the amount of fresh organic matter in the soil at the start of the season [*Matthews et al.*, 2000]. Referring to the works by *Mishra et al.* [1997] and *Matthews et al.* [2000], we simulated the changes of soil Eh during flooding or drainage course by following differential equations.

$$\begin{cases} Eh^{(t+1)} = Eh^{(t)} - D_{Eh} \\ \quad \times (A_{Eh} + \min(1, C_{OM})) \times \left(Eh^{(t)} - B_{Eh}\right) & \textit{for flooding course} \\ Eh^{(t+1)} = Eh^{(t)} - D_{Eh} \\ \quad \times (A_{Eh} + 0.7) \times \left(Eh^{(t)} - B_{Eh}\right) & \textit{for drainage course} \end{cases} \tag{14}$$

where $Eh^{(\mathrm{t})}$ represents the soil Eh value at time t. The t represents the days after flooding or since drainage. The A_{Eh} and D_{Eh} are the differential coefficients. By applying a trial-and-error optimization method to the field measurements of Eh by *Cao et al.* [1997] in Jurong and by this group in Nanjing (unpublished data), the values of A_{Eh} and D_{Eh} were determined to be 0.23 and 0.16, respectively. The B_{Eh} is a limit criterion, which takes a low-limit value of −250 mv for the flooding course and an upper-limit value of 300 mv for the drainage course, respectively. It is a bit difficult to simulate the soil Eh change for the intermittent irrigation, since the irrigation frequency changes widely for different

Table 1. Summary of the Observations for Validating the CH4MOD

Observational Site	Location	Soil Texture (Sand Percentage)	Observational Seasons	Rice Cultivation	Cases	Reference
Guangzhou, Guangdong	23°08′N, 113°20′E	sandy loam (46.3)	1994	double	4	Institute of Atmospheric Physics, CAS
Changsha, Hunan	28°09′N, 113°06′E	Sandy loam (62.0)	1995–1997	double	20	APN database
Taoyuan, Hunan	28°55′N, 110°30′E	Silty Loam (21.2)	1992	double	8	*Shangguan et al.* [1993]
Tuzu, Sichuan	29°40′N, 103°50′E	Sand (78.5)	1988–1994	single	7	*Khalil et al.* [1998]
Chongqing	29°48′N, 106°18′E	Sand (57.0)	1995–1997	single	11	APN database
Hangzhou, Zhejiang	30°19′N, 120°12′E	loam (23.0)	1995–1998	single/double	7/16	APN database
Nanjing, Jiangsu	31°51′N, 118°49′E	Clay (4.8)	1999	single	4	Program of TECO/NASA by this group
Fengqiu, Henan	35°24′N, 114°24′E	Clay (2), loam (20), sand (80)	1993–1994	single	6	APN database
Beijing	40°30′N, 116°25′E	Sand (55.0)	1995–1997	single	11	*Wang et al.* [1998]

area. Thus we assumed the soil Eh fluctuates by 10–20 mv from a constant value of −20 mv.

3. Model Validation

[19] The modified model was run with a daily step and validated against independent CH_4 emission measurements over the year from 1988 to 1999. These measurements were made in 9 sites covering five main rice cultivation regions in China, including different water regime, organic matter incorporation, and rice cropping system. A summary of the observations is given in Table 1.

3.1. Model Input

[20] Model parameter inputs include rice grain yield (*GY*), soil sand percentage (*SAND*), amount of organic amendment, initial fraction of the structural and non-structural carbohydrates of the incorporated organic matter, water management pattern, and daily air temperature (T_{air}).

[21] Rice grain yield was recorded for some but not for all of the measurements. We used the statistical average of the *GY* adjacent to the experimental site when it was not reported. The soil sand percentage was referred to the soil database developed by the Institute of Soil Sciences, Chinese Academy of Sciences when it was not reported. Types of organic matter amended into rice field at transplanting include animal manure, green manure, biogas residuals, and crop straw. Naturally addition of OM into the soil includes crop root and stubbles from previous season, and wild weeds when previous season was fallowed. If not explicitly specified, we assumed that root of the previous crop and stubbles (about 10% of the above ground biomass) were left in the soil. When the field remained fallow during the previous season, we assumed that wild weed residues would be present in the soil. According to the climate conditions, the amount of wild weeds varied from 0 (cold winter like in Beijing) to 2000 (warmer winter like in Hunan and Guangdong) kg ha^{-1} dry matter. In the double rice cropping system, 50% of the rice straw from the early-rice was assumed to be incorporated into soils of the late-rice season. The initial fractions of OM_N and OM_S for different types of organic matter are summarized in Table 2. Daily air temperature was obtained from local meteorological station. The soil temperature (T_{soil}) was estimated by air temperature (T_{air}) as $T_{soil} = 4.4 + 0.76 \times T_{air}$ [*Huang et al.*, 1998].

[22] Water management is one of the most important practices in rice cultivation. To reduce ineffective tillers, remove toxic substances and maintain healthy roots under reduced soil conditions, short periods of drainage for soil aeration during the vegetative growth period and intermittent irrigation during the reproductive growth period are commonly practiced in Japan [*Yoshida*, 1981] and China [*Gao et al.*, 1992]. The extent of drainage and the interval between the cycles of irrigation-drainage-reintroduced water vary with soil characteristics and weather conditions. In high land (rain fed), rice paddies are kept flooded by rain without irrigation [*Khalil et al.*, 1998]. Typical irrigation patterns in China according to *Gao and Li* [1992] and *Su* [2000] are summarized in Table 3. Seasonal changes in soil Eh for a given irrigation pattern were calculated by equation (14). The resulting calculated Eh was used in equation (8).

[23] Above ground biomass at transplanting (W_0) was assigned a value of 15 g m^{-2} [*Gao et al.*, 1992]. *Huang et al.* [1998] gave the value of 0.08 ± 0.02 d^{-1} for the intrinsic growing rate of rice plant (*r*). Values of r equal to 0.08 for single rice and 0.1 for early-/late-rice, respectively, were used to simulate rice growth. *Huang et al.* [1997] derived a rice variety index (*VI*) from field observations of CH_4 emission, grain yield and the *SI* for ten cultivars under permanent flooding condition. They evaluated the value of *VI* to be 1.0 for the majority of cultivars (8 out of 10) and 1.5 for high emission cultivars (2 out of 10). However, measurements of CH_4 emission for different cultivars under permanent flooding condition were not available in China. In a study by *Huang et al.*

Table 2. Initial Fractions of OM_N and OM_S in Incorporated Organic Matter

Organic Matter	OM_N	OM_S
Rice straw	0.59[a]	0.41
Rice root	0.42[a]	0.58
Wheat straw	0.49[a]	0.51
Wheat root	0.31[a]	0.69
Green manure	0.80[a,b]	0.20
Farm manure	0.25[c]	0.75
Bio-gas residues	0.10[c]	0.90

[a] Calculated from *Huang et al.* [2003].

[b] Wild weeds included.

[c] Average value and strongly dependent on fermentation of the raw material.

Table 3. Irrigation Patterns for Rice Cultivation in China[a]

Pattern Code	Irrigation Courses[b]	Description
1	F—D—F—M	single rice crop in the northern and eastern China
2	F—D—M	single and double rice crop in the southern and southwestern China
3	F—M	similar to pattern 2, without obvious drainage
4	F	high land rice fields or salty soil field
5	M	lowland, usually with high undergroundwater level

[a] Referred to *Gao and Li* [1992] and *Su* [2000].

[b] F, Flooded; D, Drained; M, moist with intermittent irrigation.

[1999], the *VI* was taken a constant of 1.0 for all cases to validate the model. Table 4 gives more detailed information about model symbols, definitions, and values/unites.

3.2. Validation for Single Rice Cultivation

[24] Single rice cultivation is prevalent in western, northern, and most of eastern China. Rotations of wheat-rice, green manure-rice, rapeseed-rice and fallow-rice are the main cropping systems in these regions. A total of 46 observations made in Beijing, Jiangsu, Zhejiang, Chongqing, Sichuan and Henan were simulated. Figure 1 shows the computed and the observed seasonal values of CH_4 emission under different water regimes with or without organic matter amendments, indicating that the model can well capture the seasonal patterns of CH_4 emissions.

3.3. Validation for Double Rice Cultivation

[25] Double rice cropping systems are mainly distributed in southern, southwestern and southeastern China where hydrological and thermal resources are more abundant. A total of 48 observations made in Guangdong, Hunan, Sichuan and Zhejiang were simulated. Figure 2 gives the simulated and observed seasonal changes in CH_4 emissions from Changsha and Taoyuan of Hunan province, Guangzhou of Guangdong province, and Hangzhou of Zhijiang province, respectively. Results in Figure 2 suggest that the

Table 4. Parameters and Constants and Their Description for CH4MOD Running

Symbol	Description	Value/Unit
	Rice Growth	
W	Aboveground biomass	Model result/g m^{-2}
W_0	Initial above ground biomass at transplanting	15/g m^{-2}
W_{max}	Aboveground biomass at harvesting	Model result/g m^{-2}
W_{root}	Root biomass	Model result/g m^{-2}
GY	Rice grain yield	Model input/g m^{-2}
r	Intrinsic growth rate of rice plant	0.08/d^{-1} for single rice 0.1/d^{-1} for early-/late-rice
	Methanogenic Substrates	
C_R	Carbohydrates derived from rice root exudation	Model result/g m^{-2} d^{-1}
C_{OM}	Carbohydrates derived from OM decomposition	Model result/g m^{-2} d^{-1}
OM	Organic matter	Model input/g m^{-2}
OM_N	Non-structural component of OM	Model result/g m^{-2}
OM_S	Structural component of OM	Model result/g m^{-2}
k_1	First order decay rate of OM_N	2.7×10^{-2}/d^{-1}
k_2	First order decay rate of OM_S	3.0×10^{-3}/d^{-1}
VI	Rice variety index	1.0/dimensionless
	Methane Production and Emission	
P	CH_4 production	Model result/g m^{-2} d^{-1}
P_0	Criterion of CH_4 production when CH_4 bubbles occur	0.002/g m^{-2} d^{-1}
F_p	CH_4 emitted fraction via rice plant	Model result/dimensionless
E_p	CH_4 emitted via rice plant	Model result/g m^{-2} d^{-1}
E_{bl}	CH_4 emitted via bubbles	Model result/g m^{-2} d^{-1}
	Environments and Derivatives	
SAND	Soil sand	Model input/%
T_{air}	Air temperature	Model input/°C
T_{soil}	Soil temperature	Model result/°C
Eh	Soil redox potential	Model result/mv
Q_{10}	Temperature coefficient	3.0/Dimensionless
SI	Soil texture index	Model result/Dimensionless
TI	Soil temperature index	Model result/Dimensionless
F_{Eh}	Soil Eh index	Model result/Dimensionless
A_{Eh}	Deferential coefficient of soil Eh	0.23/mv
D_{Eh}	Deferential coefficient of soil Eh	0.16/Dimensionless
B^{Eh}	Low and up limit for soil Eh	−250/mv for flooding regime 300/mv for drainage regime

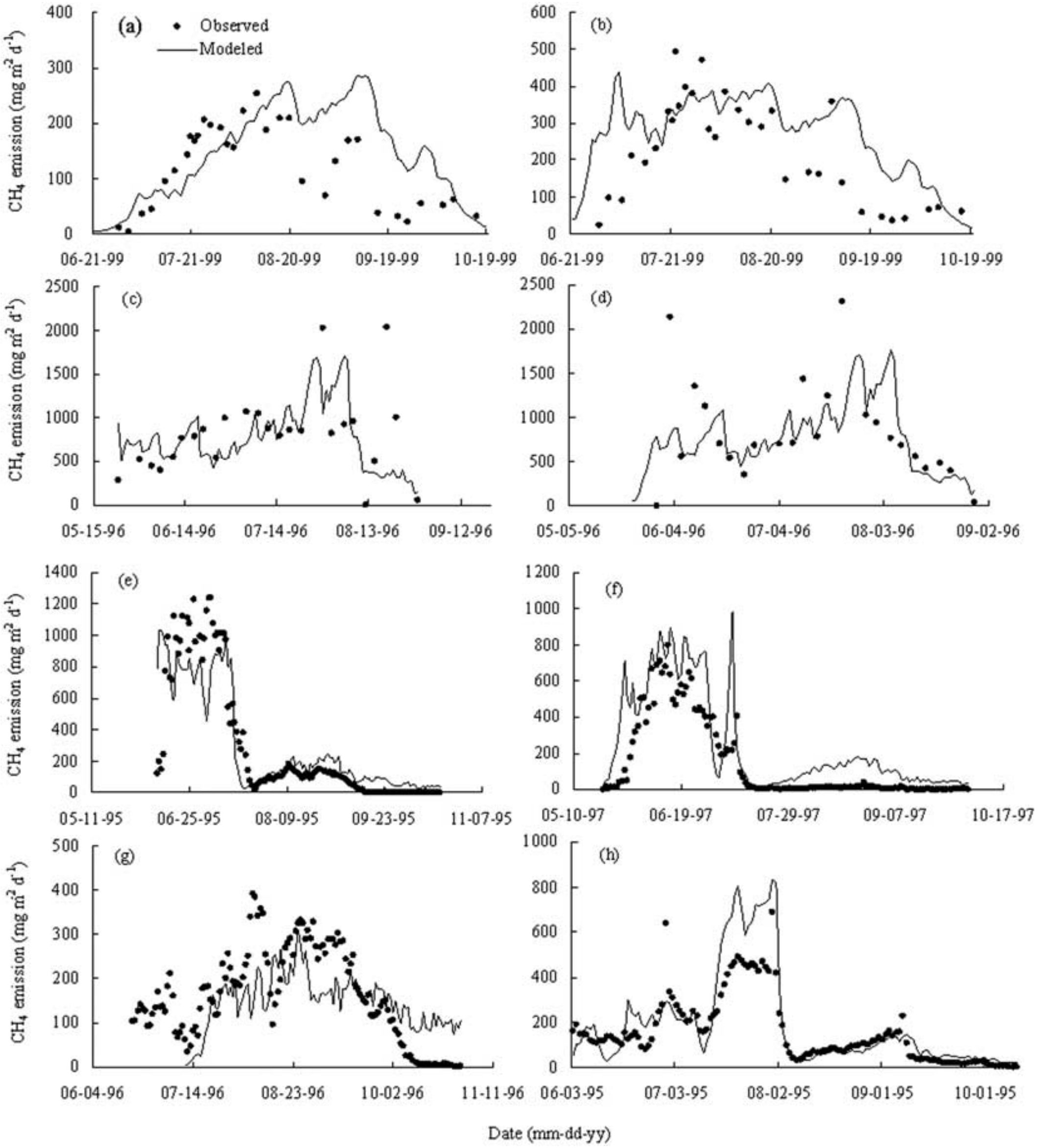

Figure 1. Comparison of simulated with observed seasonal patterns of methane emission from single rice paddies with diverse agricultural practices. (a) Nanjing1999, irrigation ptn-4, no OM amendment, wheat/rice; (b) Nanjing1999, irrigation ptn-4, wheat straw 4.5 t ha^{-1}, wheat/rice; (c) Chongqing1996, irrigation ptn-3, farm manure 5.0t ha^{-1}, waterlog/rice; (d) Chongqing1996, irrigation ptn-3, farm manure 5.0t ha^{-1}, wheat/rice; (e) Beijing1995, irrigation ptn-2, pig manure 3.6t ha^{-1}, wheat/rice; (f) Beijing1997, irrigation ptn-2, rice straw 2.6t ha^{-1}, fallow/rice; (g) Hangzhou1996, irrigation ptn-3, no OM amendment, fallow/rice; (h) Hangzhou1995, irrigation ptn-1, green manure 1.1 t ha^{-1}, fallow/rice.

present model could well simulate CH$_4$ emissions from early- and late-rice cultivation under different water regimes with or without organic matter amendments.

3.4. Validation of Total Seasonal CH$_4$ Emission

[26] Total simulated seasonal CH$_4$ emission values were determined from the summation of simulated daily values. Observed and modeled total seasonal CH$_4$ estimation for each case is given in Table 5. The observed seasonal amount ranged from 3.1 to 761.7 (kg C ha^{-1}) with an average of 199.4 ± 187.3 (kg C ha^{-1}). In consonance with the observations, simulations with the model result in an average value of 224.6 ± 187.0 (kg C ha^{-1}), ranging from 13.9 to 824.3 (kg C ha^{-1}). The regression of computed against observed emissions (Figure 3) yields an r^2 of 0.84 with a slope of 0.92 and an intercept of 41.1 ($n = 94$, $P < 0.001$).

4. Model Significance of the Bubble Flux for Overall Emissions and the Drainage Effect on CH$_4$ Production/Emission

4.1. Model Significance of the Bubble Flux for Overall Emissions

[27] Methane emission via bubbles was observed from rice fields [*Bartlett et al.*, 1988; *Wilson et al.*, 1989;

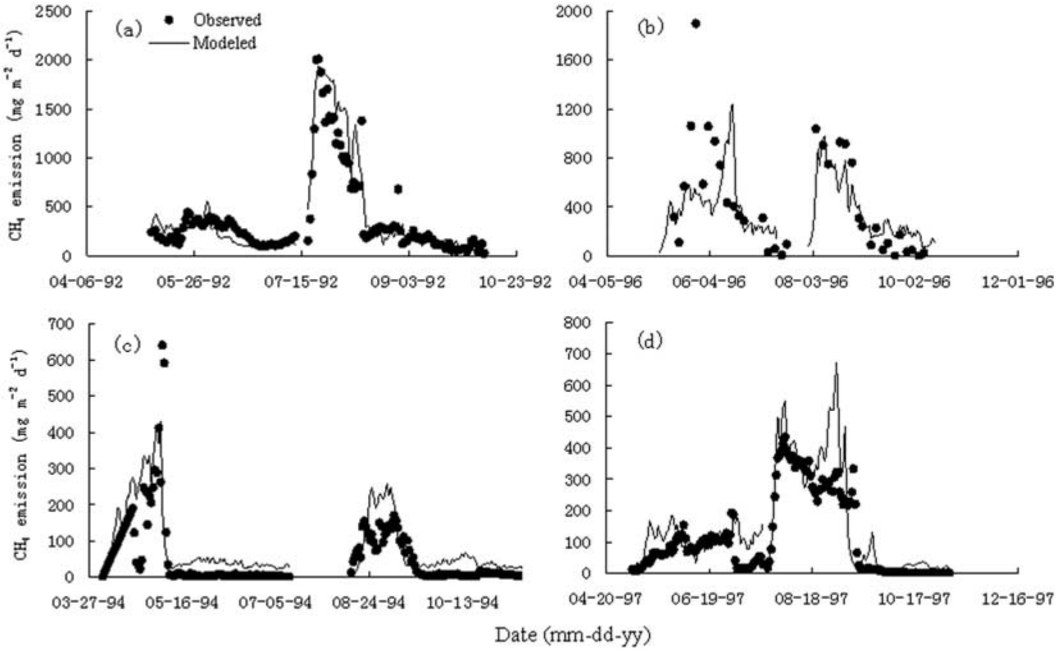

Figure 2. Comparison of simulated with observed seasonal patterns of methane emission from double rice paddies. (a) Taoyuan1992, early-rice: green manure 3t ha^{-1}, farm manure 1.9t ha^{-1}, irrigation ptn-3; late-rice: rice straw 4.5t ha^{-1}, farm manure 1.9t ha^{-1}, irrigation ptn-3; (b) Changsha1996, early-rice: wild weeds 0.46t ha^{-1}, irrigation ptn-3; late-rice: no OM amendment, irrigation ptn-3; (c) Guangzhou1994, early-rice: farm manure 3t ha^{-1}, irrigation ptn-3; late-rice: no OM amendment, irrigation ptn-3; (d) Hangzhou1997, early-rice: Bio-gas residual 0.6t ha^{-1}, irrigation ptn-3; late-rice: Bio-gas residual 0.6t ha^{-1}, irrigation ptn-1.

Shangguan et al., 1993]. Observations made in Hunan province of China by *Shangguan et al.* [1993] indicated that the contribution of CH$_4$ emitted via bubbles to the overall emissions accounted for 24% for the early-rice and 55% for the late-rice cropping, respectively. Model simulation for 94 cases suggested that the bubble flux contribute 5%–45% to the overall emissions. Figure 4 shows the computed seasonal variations in plant-mediated CH$_4$ emission and bubble flux. Calculations indicated that bubble flux from the single rice cropping system accounted for 11% in Hangzhou (Figure 4a) and 27% in Beijing (Figure 4b), respectively. With respect to the double rice cropping system, the bubble fluxes contributed 23.5% for the early-rice and 32.5% for the late-rice cropping in Taoyuan (Figure 4c), and 18.4% for the early-rice and 28.6% for the late-rice cropping in Changsa (Figure 4d), respectively. Clearly, the bubble fluxes simulated by the revised model fall into the range of field observations [*Shangguan et al.*, 1993].

[28] It is well recognized that plant-mediated transport through micropores in rice leaf sheaths is the primary mechanism for CH$_4$ emission [*Nouchi*, 1994]. In the early growing period, however, CH$_4$ emission via rice plants might be restricted due to fewer micropores, and hence the bubble flux plays a key role, especially when a relatively high amount of organic matter is incorporated into the soil (Figures 4b and 4c). Higher temperature during the early growing period of late-rice cropping enhanced decomposition of organic matter, which is favorable for CH$_4$ production and consequently emission via bubbles (Figures 4c and 4d). Obviously, the modified model captures the signals of bubble fluxes (Figure 4) and the simulated overall emissions agreed well with observations (Figures 1e, 2a, and 2b). Since the original model included no such function, overall emissions might have been underestimated by the original model, particularly when additional organic matter was incorporated and during periods of higher temperatures (Figures 4b–4d).

4.2. Model Significance of the Drainage Effect on CH$_4$ Production/Emission

[29] It has been well documented that periodic drainage of irrigated rice paddies usually results in a significant decrease in methane emissions. Field observations indicated that intermittent irrigation system resulted in some 64% decrease in CH$_4$ emissions [*Yang and Chang*, 2001]. *Mishra et al.* [1997] reported the reduction factors of 45% to 72% by setting different courses of periodic drainage in their pot experiment. According to the review of *Cai* [1997], mid-season aeration during the period of rice growth could mitigate CH$_4$ emission by as much as 50%.

[30] We computed the CH$_4$ emissions under conditions of irrigation pattern-1, pattern-2, pattern-3 and continuous flooding (see Table 3), respectively. These calculations indicate that CH$_4$ emission from a single rice cropping system decreased 59% with irrigation pattern-1 in Hangzhou (Figure 5a) and 55% with irrigation pattern-2 in Beijing (Figure 5b), respectively. For the double rice cropping system in Taoyuan, calculations for irrigation pattern-3 resulted in 45% and 37% decrease in CH$_4$ emissions for the early-rice and the late-rice cropping (Figure 5c), respectively. Apparently, the simulated reduction in CH$_4$ emission

Table 5. Detailed Information on the Field Observations and Model Results

Case Code	Transplanting (yyyy-mm-dd)	Harvesting (yyyy-mm-dd)	Yield, g m^{-2}	I.P.[a]	Previous Season	OM Amendment (t ha^{-1}, dry weight)	Observed CH$_4$ (kg C ha^{-1})	Modeled CH$_4$ (kg C ha^{-1})
BJ1995_T1	1995-06-04	1995-10-17	649	2	Wheat	Pig manure 3.6	273.74	281.44
BJ1995_T2	1995-06-04	1995-10-17	648	5	Wheat	Pig manure 3.6	150.28	181.07
BJ1995_T3	1995-06-04	1995-10-17	561	4	Wheat	Pig manure 3.6	361.19	622.08
BJ1995_T4	1995-06-04	1995-10-17	543	2	Wheat		19.30	110.88
BJ1996_T1	1996-05-25	1996-10-08	770	2	Fallow		16.86	53.95
BJ1996_T2	1996-05-25	1996-10-08	680	2	Fallow		36.67	53.95
BJ1996_T3	1996-05-25	1996-10-08	690	2	Fallow		32.88	53.95
BJ1997_T1	1997-05-22	1997-10-06	774	2	Fallow	Pig manure 2.6	144.77	199.72
BJ1997_T2	1997-05-22	1997-10-06	667	2	Fallow	Cattle manure 2.6	32.32	139.95
BJ1997_T3	1997-05-22	1997-10-06	694	2	Fallow	Rice straw 2.6	106.92	200.12
BJ1997_T4	1997-05-22	1997-10-06	694	2	Fallow		4.33	68.88
CS1995_HFe	1995-05-08	1995-07-14	600[b]	3	Fallow	Wild weeds 1.0	134.38	182.54
CS1995_HFL	1995-07-24	1995-10-20	600[b]	3	Early-rice		206.59	208.09
CS1995_HMe	1995-05-08	1995-07-14	600[b]	3	Green Manure	Green manure 0.75	102.40	166.65
CS1995_HML	1995-07-24	1995-10-20	600[b]	3	Early-rice		92.10	196.09
CS1996_HFe	1996-05-05	1996-07-14	600[b]	3	Fallow	Wild weeds 0.46	252.28	197.82
CS1996_HFL	1996-07-31	1996-10-15	600[b]	3	Early-rice		189.68	191.81
CS1996_HMe	1996-05-05	1996-07-14	600[b]	3	Green Manure	Green manure 2.6	219.50	267.82
CS1996_HML	1996-07-31	1996-10-15	600[b]	3	Early-rice		52.63	222.94
CS1996_HRe	1996-05-05	1996-07-14	600[b]	3	Rapeseed Plant	Rapeseed plant straw 5.4	625.47	395.24
CS1996_HRL	1996-07-31	1996-10-15	600[b]	3	Early-rice		304.53	246.94
CS1996_HSe	1996-05-05	1996-07-14	600[b]	3	Waterlog		240.88	151.45
CS1996_HSL	1996-07-31	1996-10-15	600[b]	3	Early-rice		159.98	181.55
CS1997_HFe	1997-050-6	1997-07-14	600[b]	3	Fallow	Wild weeds 0.9	137.54	173.68
CS1997_HMe	1997-05-06	1997-07-14	600[b]	3	Green Manure	Green manure 2.5	232.55	247.93
CS1997_HRe	1997-05-06	1997-07-14	600[b]	3	Rapeseed Plant	Rapeseed plant straw 2.2	396.00	237.01
CS1997_HSe	1997-05-06	1997-07-14	600[b]	3	Green Manure		191.14	138.51
CS1997_HFL	1997-07-31	1997-10-20	600[b]	3	Early-rice		89.88	215.06
CS1997_HML	1997-07-31	1997-10-20	600[b]	3	Early-rice		190.10	221.74
CS1997_HRL	1997-07-31	1997-10-20	600[b]	3	Early-rice		461.86	241.65
CS1997_HSL	1997-07-31	1997-10-20	600[b]	3	Early-rice		69.94	196.33
FQ1993_Pn	1993-06-28	1993-10-14	765	5	Fallow	Farm manure 1.1	3.10	13.93
FQ1993_Pr	1993-06-28	1993-10-14	810	5	Fallow	Farm manure 1.1	13.98	31.10
FQ1993_Ps	1993-06-28	1993-10-14	471	5	Fallow	Farm manure 1.1	8.86	86.74
FQ1994_Pn	1994-06-21	1994-10-07	765	5	Fallow	Farm manure 1.3	8.79	17.33
FQ1994_Pr	1994-06-21	1994-10-07	810	5	Fallow	Farm manure 1.3	12.20	38.11
FQ1994_Ps	1994-06-21	1994-10-07	471	5	Fallow	Farm manure 1.3	36.16	105.07
GZ1994_T1e	1994-04-03	1994-07-13	640	2	Fallow	Farm manure 3.0	45.31	72.97
GZ1994_T1L	1994-08-14	1994-11-18	640	3	Early-rice		29.25	32.19
GZ1994_T2e	1994-04-03	1994-07-13	640	2	Fallow		15.10	33.20
GZ1994_T2L	1994-08-14	1994-11-18	640	3	Early-rice		25.22	32.42
HZ1995_T1	1995-05-30	1995-10-10	663	2	Fallow		162.18	159.06
HZ1995_T2	1995-05-30	1995-10-10	620	1	Fallow	Green manure 1.1	152.04	184.07
HZ1995_T3	1995-05-30	1995-10-10	649	2	Fallow	Green manure 1.1	242.67	210.57
HZ1995_T4	1995-05-30	1995-10-10	668	4	Fallow	Green manure 1.1	334.36	447.33
HZ1996_T1	1996-06-20	1996-10-30	521	3	Fallow		137.24	130.48
HZ1996_T2e	1996-05-08	1996-07-24	515	3	Fallow		68.35	70.69
HZ1996_T2L	1996-07-26	1996-11-07	505	3	Early-rice		75.03	148.25
HZ1996_T3	1996-06-20	1996-09-26	560	3	Fallow		126.31	99.71
HZ1996_T4e	1996-05-08	1996-07-24	493	3	Fallow		63.53	69.59
HZ1996_T4L	1996-07-26	1996-10-30	505	3	Early-rice		84.16	139.84
HZ1997_T1e	1997-05-04	1997-07-20	627	3	Fallow		40.55	59.29
HZ1997_T1L	1997-07-22	1997-11-07	633	1	Early-rice		108.37	136.59
HZ1997_T2e	1997-05-04	1997-07-20	627	3	Fallow	Farm manure 0.9	44.84	69.54
HZ1997_T2L	1997-07-22	1997-11-07	633	1	Early-rice	Farm manure 0.9	136.96	158.64
HZ1997_T3	1997-06-10	1997-09-20	624	1	Fallow		66.61	78.37
HZ1997_T4e	1997-05-04	1997-07-20	627	3	Fallow	Biogas residual 0.6	40.12	61.73
HZ1997_T4L	1997-07-22	1997-11-07	633	1	Early-rice	Biogas residual 0.6	115.36	146.82
HZ1998_T1e	1998-04-29	1998-07-17	620	3	Fallow		106.39	67.63
HZ1998_T1L	1998-07-21	1998-11-07	631	3	Early-rice		138.65	166.48
HZ1998_T2e	1998-04-29	1998-07-17	616	3	Fallow	Rice straw 1.1	168.36	92.27
HZ1998_T2L	1998-07-21	1998-11-07	631	3	Early-rice	Rice straw 1.1	209.52	239.65
HZ1998_T4e	1998-04-29	1998-07-17	613	3	Fallow	Rice straw 1.1	150.19	92.25
HZ1998_T4L	1998-07-21	1998-11-07	631	3	Early-rice	Rice straw 1.1	185.77	239.73
NJ1999_D0	1999-06-21	1999-10-20	750	2	Wheat		102.56	28.17
NJ1999_D2	1999-06-21	1999-10-20	750	2	Wheat	Wheat straw 4.5	84.93	197.81
NJ1999_F0	1999-06-21	1999-10-20	750	4	Wheat		90.68	128.03
NJ1999_F2	1999-06-21	1999-10-20	750	4	Wheat	Wheat straw 4.5	148.34	231.97
TY1992_T1e	1992-05-01	1992-07-13	584[b]	3	Fallow	Green manure 3.0	99.57	96.98
TY1992_T1L	1992-07-15	1992-10-09	584[b]	3	Early-rice	Farm manure 0.9; Rice straw 1.5	224.84	194.21
TY1992_T2e	1992-05-01	1992-07-13	584[b]	3	Fallow	Green manure 3.0; Farm manure 1.9	118.35	113.99
TY1992_T2L	1992-07-15	1992-10-09	584[b]	3	Early-rice	Farm manure 1.9; Rice straw 4.5	297.61	349.45

Table 5. (continued)

Case Code	Transplanting (yyyy-mm-dd)	Harvesting (yyyy-mm-dd)	Yield, g m^{-2}	I.P.[a]	Previous Season	OM Amendment ($t\ ha^{-1}$, dry weight)	Observed CH_4 ($kg\ C\ ha^{-1}$)	Modeled CH_4 ($kg\ C\ ha^{-1}$)
TY1992_T3e	1992-05-01	1992-07-13	584[b]	3	Fallow		37.30	46.63
TY1992_T3L	1992-07-15	1992-10-09	584[b]	3	Early-rice		50.20	60.52
TY1992_T4e	1992-05-01	1992-07-13	584[b]	3	Fallow	Biogas residual 7.5	123.17	85.87
TY1992_T4L	1992-07-15	1992-10-09	584[b]	3	Early-rice	Biogas residual 7.5	153.18	184.59
TZ1988	1988-04-20	1988-08-22	500	3	Oilseed plant	Farm manure 6.1	722.95	781.41
TZ1989	1989-04-20	1989-08-26	487	3	Oilseed plant	Farm manure 6.2	490.54	692.62
TZ1990	1990-05-01	1990-08-19	470	3	Oilseed plant	Farm manure 6.4	761.70	727.65
TZ1991	1991-04-23	1991-08-25	545	2	Oilseed plant	Farm manure 7.7	460.63	443.73
TZ1992	1992-05-01	1992-08-24	672	3	Oilseed plant	Farm manure 10.0	558.31	602.73
TZ1993	1993-05-02	1993-08-29	543	2	Oilseed plant	Farm manure 9.2	690.71	824.33
TZ1994	1994-04-26	1994-08-19	471	3	Oilseed plant	Farm manure 5.3	607.51	628.46
CQ1995_T1	1995-05-15	1995-08-23	613[b]	3	Waterlog		260.77	327.79
CQ1995_T2	1995-05-15	1995-08-23	613[b]	3	Waterlog		302.33	327.79
CQ1995_T3	1995-05-15	1995-08-23	613[b]	3	Wheat		89.76	340.09
CQ1996_T1	1996-05-23	1996-09-02	613[b]	3	Waterlog	Farm manure 5.0	662.92	570.52
CQ1996_T2	1996-05-23	1996-09-02	613[b]	3	Waterlog		608.02	570.52
CQ1996_T3	1996-05-23	1996-09-02	613[b]	3	Wheat	Farm manure 5.0	444.18	565.99
CQ1996_T4	1996-05-23	1996-09-02	613[b]	3	Wheat		593.97	565.99
CQ1997_T1	1997-05-10	1997-08-19	613[b]	3	Waterlog		309.94	362.32
CQ1997_T2	1997-05-10	1997-08-19	613[b]	3	Waterlog		335.25	362.32
CQ1997_T3	1997-05-10	1997-08-19	613[b]	3	Wheat		345.53	359.31
CQ1997_T4	1997-05-10	1997-08-19	613[b]	3	Wheat		336.21	359.31

[a] Irrigation pattern.

[b] Estimated as local average.

induced by drainage events is comparable to observed values.

5. Discussion

5.1. Advantages and Disadvantages of Mechanistic and Empirical Models

[31] Methane emission from rice cultivation is among the most uncertain estimates of the agricultural sector in rice-growing countries. Reduction in the uncertainties might be achieved by coupling field-scale model estimates to regional databases. A model developed for this purpose should be reliable, and allow extrapolation with input parameters that are commonly available. Several models have been developed to estimate CH_4 emission from rice paddies over the last decade. Some of these models [*Cao et al.*, 1995; *Arah and Stephen*, 1998; *Li et al.*, 1994; *Li*, 2000; *Matthews et al.*, 2000; *Bodegom et al.*, 2001] are mechanistic, and others [*Bachelet and Neue*, 1993; *Huang et al.*, 1998] are more empirical. Both mechanistic and empirical models have their advantages and disadvantages. Reliability of the models, either mechanistic or empirical, is more likely dependent on whether the observations in situ can be properly described or not.

[32] Mechanistic models combine available knowledge with the processes of CH_4 production, oxidation and emission. The advantage of mechanistic models is that they have a theoretical foundation, and thus the model estimates should be reliable at least on a regional scale. However, like all models, mechanistic models have several limitations. Some mechanistic models need site-specific parameters, and some could properly simulate a given field measurement but the simulated components are not comparable with other field observations, which makes it hard to extrapolate these models to a wide scale. For example, a mechanistic model developed by *Cao et al.* [1995] needs model inputs of seasonal patterns of soil Eh and floodwater depth for simulating CH_4 emission from rice paddies. *Matthews et al.* [2000] developed a mechanistic model in which CH_4 production is associated with the soil pH, temperature, the presence of other ions (i.e., NO_3^-, Fe^{3+}, Mn^{4+}, SO_4^{2-}), and the concentration of O_2 in the soil. The plant-mediated CH_4 transport, emissions via diffusion and ebullition were simulated in their model. They validated their model against two cases of field measurement, and a generally good agreement between computed and observed overall CH_4 flux was documented. However, the modeled proportion of CH_4 produced that is then oxidized constitutes only some 7% of the seasonal total [*Matthews et al.*, 2000], while experiments from Italian rice fields [*Schütz et al.*, 1989b] and American rice fields [*Sass et al.*, 1990, 1992] showed that the oxidized fraction varied from 0.45 to 0.95 over the growing season.

[33] Empirical models are mainly developed from statistical analysis and an integration of in situ signals. The

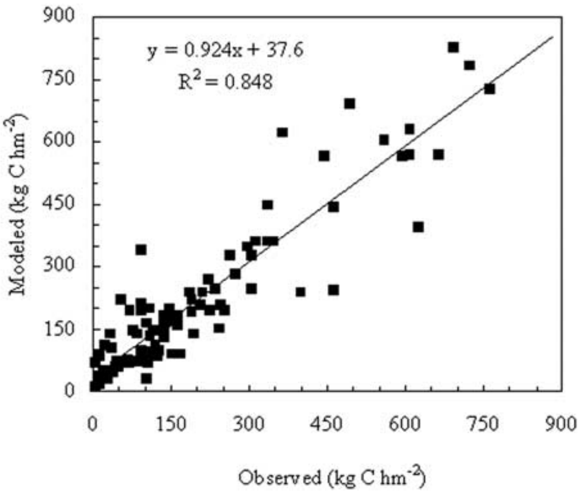

Figure 3. Comparison of simulated with measured total seasonal methane emissions from rice paddies with diverse agricultural practices across China.

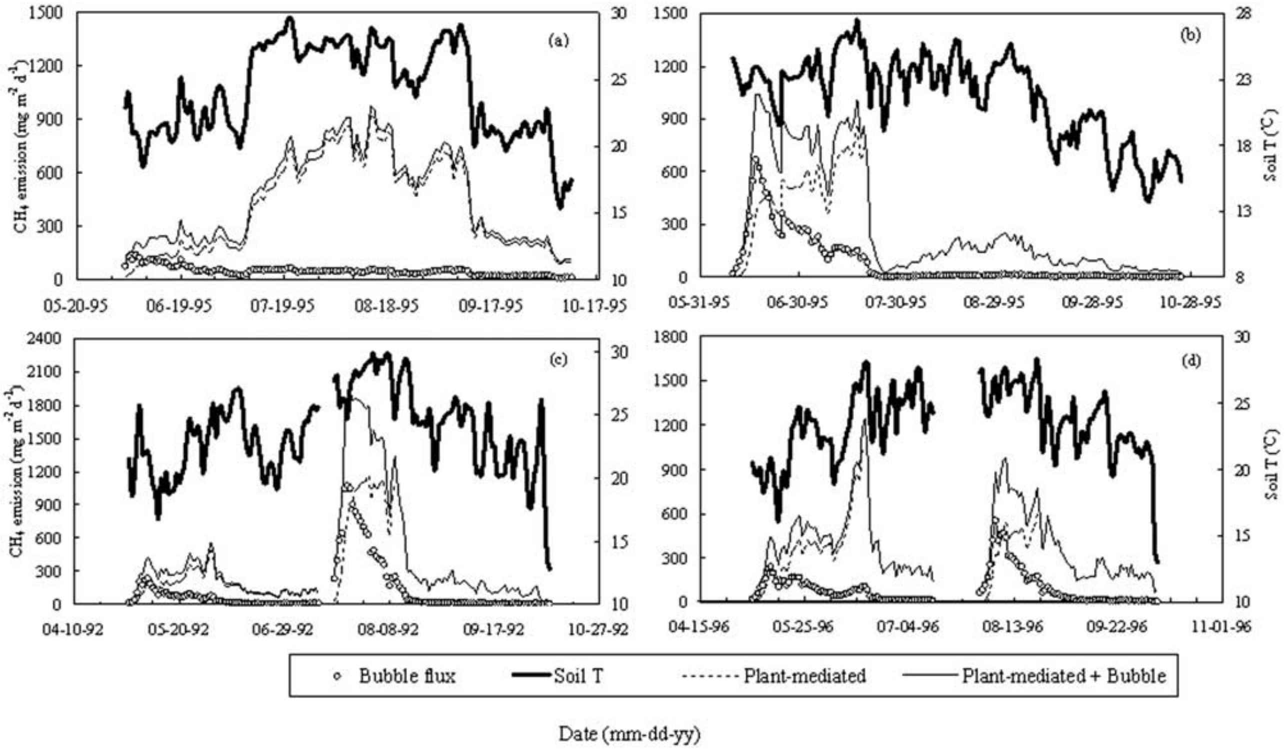

Figure 4. Computed seasonal variations in plant-mediated CH_4 emission and bubble flux. (a) Hangzhou1995, green manure 1.1t ha^{-1}, irrigation ptn-4, fallow/rice; (b) Beijing1995, pig manure 3.6t ha^{-1}, irrigation ptn-2, wheat/rice; (c). Taoyuan1992, early-rice: green manure 3.0t ha^{-1}; farm manure 1.9t ha^{-1}, irrigation ptn-3; late-rice, farm manure 1.9t ha^{-1} + rice straw 4.5t ha^{-1}, irrigation ptn-3, (d). Changsha1996, early-rice: wild weeds 0.46t ha^{-1}, irrigation ptn-3; late-rice: no OM amendment, irrigation ptn-3.

advantage of empirical models is that they need only few input parameters. Results of empirical models are however difficult to extrapolate beyond the area for which they were developed or validated. In this study, validation against field observations covered main rice cultivation regions from northern (Beijing, 40°30′N, 116°25′E) to southern (Guangzhou, 23°08′N, 113°20′E) China, and from eastern (Hangzhou, 30°19′N, 120°12′E) to southwestern (Tuzu, 29°40′N, 103°50′E) China with various agricultural practices (Table 5). Resulting values suggest that the present model is of great potential for up scaling purposes when spatial databases on climate, soils, agronomic practices and crop grain yields are available.

5.2. New Features and Advantages of the Present Model

[34] New features of the present model are the incorporation of bubble flux process and the drainage events into the original model. Overall, the advantages of this model make it particularly applicable to the simulation of CH_4 emissions from irrigated rice fields with few input parameters of irrigation patterns, type and amount of organic matter amendment, rice grain yield, air temperature, and soil sand percentage (Table 4).

5.3. Future Requirements to Obtain Greater Accuracy in Model Estimates

[35] It is well established that cultivar type can significantly affect CH_4 emissions [*Huang et al.*, 1997]. The model dependence of CH_4 production and emission on rice cultivar (equation (2)) will be problematic in applying it on a large scale, since we are not able to quantify the VI due to unavailability of emissions data for different cultivars in China. However, the VI should be incorporated into the model to keep the model intact. When the VI is available, the model will be able to logically simulate the dependence of CH_4 production and emission on rice cultivar, even though no variety effects are currently included. Recent work by *Ding et al.* [1999] indicated that plant height or certain aspects of the rice canopy geometry might be an indicator of the variety index (VI), which would allow the model to be more easily applied in cases where varietal data are lacking.

[36] Nitrogen fertilizers are commonly used in rice cultivation to increase crop yields. Urea and ammonium sulfate account for 80–90% of the total nitrogen fertilizer required in rice cultivation [*FAO*, http://apps.fao.org/]. The influences of these inorganic fertilizers on methane emission from rice fields, however, are not well understood and reported observations about it are not consistent. *Lindau et al.* [1991] showed an increased methane emission rate with increased urea application, but *Wang et al.* [1993] reported that no change over the control for urea application and a decrease in methane production with ammonium nitrate. *Liou et al.* [2003] reported that CH_4 emission rates from the potassium nitrate plots were 1.5–3.7-fold higher than that from the ammonium sulfate plots throughout the growth period. Clearly, the effect of inorganic nitrogen on CH_4 emission

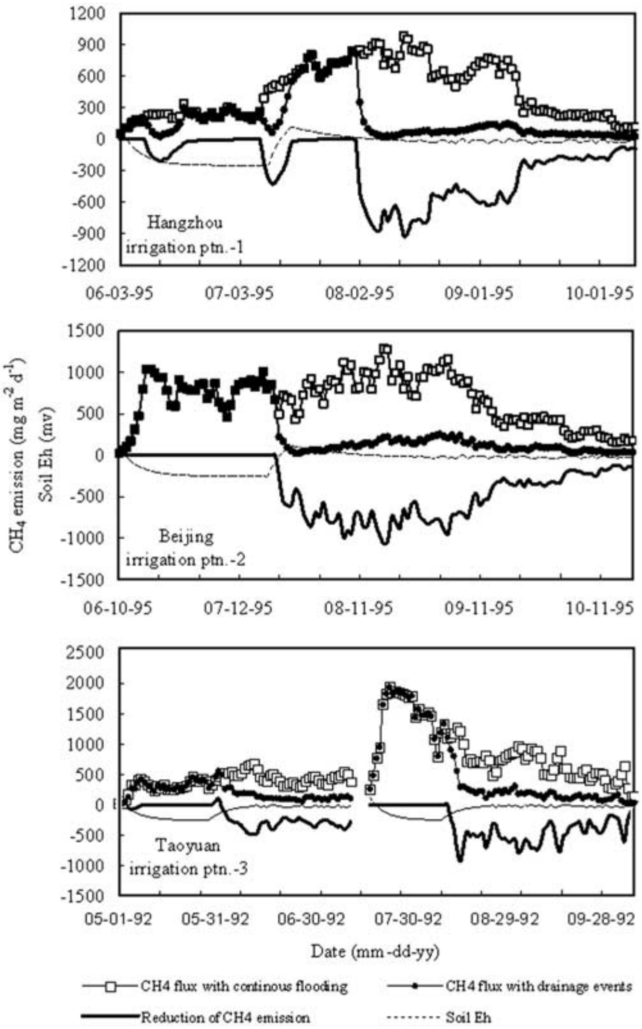

Figure 5. Computed seasonal variations in CH_4 emission with different irrigation courses.

will need to be more carefully characterized before modeling of the process can be accomplished.

[37] As our knowledge of the processes involved in CH_4 emission from rice paddies increase, models will become more mechanistic. The ultimate goal of this type of model should be to accurately calculate CH_4 emissions on a regional or larger scale based on available geographic information system data sets and remotely sensed data.

6. Conclusion

[38] Compared with the original model developed by *Huang et al.* [1998], the modified model, CH4MOD, can reasonably simulate the effect of water regime on CH_4 production/emission and the CH_4 transport via bubbles. Model validation against independent observations demonstrated that the present model is capable of simulating CH_4 emissions from irrigated rice fields with a minimal amount of inputs and parameters. A further conclusion is that the model is of great potential for up scaling as it has provided a realistic estimate of the observed results from various soils, climates and agricultural practices.

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