Model for Methane Emission from Rice Fields and Its Application in Southern China

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Received May 26,1995; revised August 2, 1995

ABSTRACT

A process model has been developed. The model has been used to calculate the methane emission from rice fields. The influence of climate conditions, field water management, organic fertilizers and soil types on methane emission from rice fields are considered. There are three major segments which are highly interactive in nature in the model: rice growth, decomposition of soil organic matter and methane production, transport efficiency and methane emission rate. Explicit equations for modeling each segment mentioned above are given. The main results of the model are: 1. The seasonal variation of methane emission of the model output agrees with that of field experiments. The deviation of seasonal average methane emission rate between modeled value and experimental data is about 10%. 2. In the whole rice growing period, model output is similar to experimental data in the seasonal variation of transport ability of rice plant. 3. Soil organic matter content and soil physics and chemistry are major factors that determine the total season average emission rate, while soil temperature controls the temporal variation of methane emission from rice fields.

Key words: Methane, Model, Rice field, Rice growth

I. INTRODUCTION

The atmospheric concentrations of CH_4, N_2O, which are so–called greenhouse gases(GHG), like CO_2, have shown large increases within the past two decades. Methane is the second most important GHG and its atmospheric concentration is currently increasing at about 0.8% yr^{-1}(13bbpv / yr) (IPCC IS92) which may be contributing to the hypothetical global warming. Cultivated wetland rice is one of the major anthropogenic sources of CH_4 and its emission to the atmosphere is estimated to be about 60(20–100)$Tgyr^{-1}$(IPCC IS92).

In order to properly evaluate the influence of human activities on global climate change, the impact of anthropogenic activities on the change of atmospheric composition must be understood first. Up to present, numerous experiments have been made to study the relationship between CH_4 emission and the parameters of the atmosphere and the soil in typical regions, as well as the processes involved in CH_4 production, oxidation and transportation. Based on a large number of experiments, a numerical model has been developed to describe the CH_4 cycle in the rice ecosystem. By inputting parameters related to the atmosphere, soil(organic matter and acidity) and fertilizer application(type and amount), the seasonal variation of methane emission from various rice culture regions will be simulated.

II. MODEL DESCRIPTION

The flooded paddy fields showed an oxic water table and soil surface. Below, the soil conditions were anoxic and reduced. Additionally, there are oxidized zones around the rice roots. Under the anoxic, reduced soil conditions, anaerobic bacteria produce simple organic acid. The methanogenic bacteria can only utilize a limited number of substrates for production of CH_4 and growth, e.g., H_2/CO_2, fomate, methanol, methylamines, acetate(Zeikus, 1977). Acetate and H_2/CO_2 seem to be the two most important methanogenic substrates in anoxic paddy soil(Takai, 1970). There are three processes of CH_4 releasing into the atmosphere from rice paddies. CH_4 loss as bubbles from soils is a common and significant mechanism. Diffusion loss of CH_4 across the water surface is another process. The third, CH_4 transport through rice plants, which has been reported(Seiler et al., 1984; Cicerone et al., 1983; Minami and Yagi, 1988; Nouchi et al., 1990), as the most important process.

For the process of CH_4 production, transport and emission shown above, rice growth, decomposition of soil organic matter, CH_4 production, transport efficiency and emission rate should be simulated in the model(see Fig. 1.).

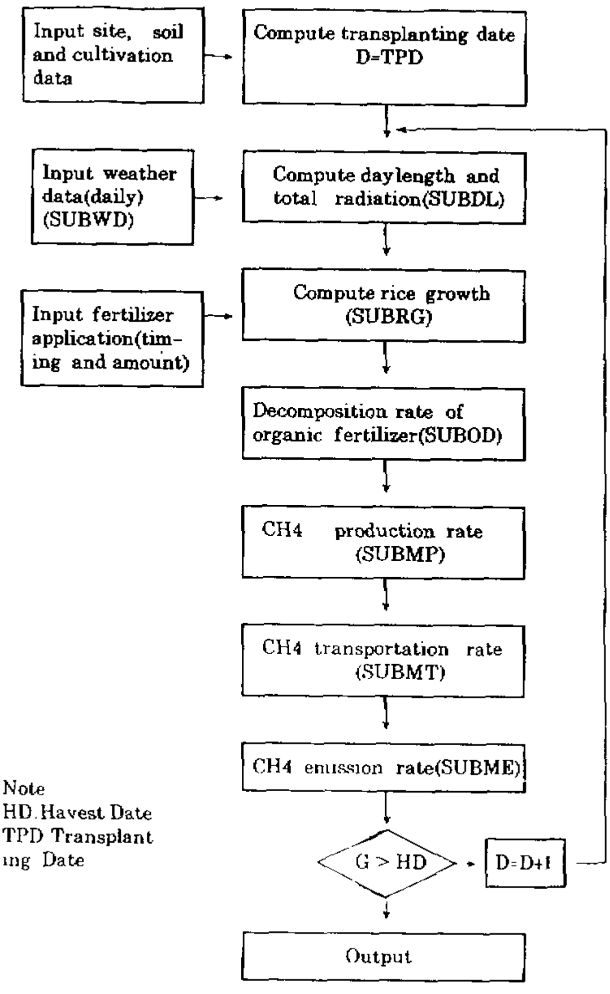

Fig. 1. Flow chart of the model.

1. *Model Assumptions*

The ultimate CH_4 cycle in rice ecosystem simulation model should be simple yet comprehensive enough to simulate CH_4 emission from different rice fields under any agroclimatic condition. At present several major simplifying assumptions have been made:

- The crop is irrigated and luxury levels of plant nutrients are present,
- Methane is produced from two carbon sources: (a) the carbon initially in the soil and provided by organic fertilizers and (b) carbon provided by the plant itself(root exudate and decayed roots),
- Methanogenesis takes place in the anaerobic layer where conditions are favorable for methane production (Eh <-200 mv),
- Reaction rate for methane production follows the Arrhenius equation.
- Methane is transported to the atmosphere through three processes: (1) rice plant, (2) soil diffusion and (3) bubbles,
- The process of methane diffusion through oxidized layer follows the diffusion–reaction equations of gas–liquid reaction.

2. *Rice Plant Development*

Rice growth is simulated based on rice model(Mcmennamy et al. 1983). It is a simplified process model for simulating the growth and yield of irrigated rice in relation to temperature, solar radiation and carbon dioxide concentration in the atmosphere. The model was developed by a rational simplification of the underlying physiological and physical process of the growth of the rice crop. Because of this, it requires only a limited number of crop parameters which can easily be obtained from well defined field experiments and hence, is applicable to a wide range of environments. In the model, the process rate is a function of photosynthetically active radiation (PAR) incidence per unit leaf area in the 400 to 700 nm waveband. The function is assumed to fit the rectangular hyperbolic curve described by the following equation(Mcmennamy et al., 1983):

$$P=\frac{1}{\dfrac{1}{PMAX}+\dfrac{1}{\gamma I}}\quad . \tag{1}$$

in which I is hourly PAR(cal cm^{-2}). P is hourly carbon dioxide exchange rate (gCO_2m^{-2}), $PMAX$ is maximum hourly carbon dioxide exchange rate as I approaches infinity, and γ is initial slope of the response curve. Detail information about the rice model can be found in the rice model (Mcmennamy, 1983).

3. *Organic Matter Decomposition*

The rate of microbial decomposition of organic material (plant or animal residues, or soil organic matter) can be calculated by a mathematical model (Parnas, 1975). The major assumptions of the model is that the rate of decomposition of any substrate is proportional to the growth rate of its decomposers. It is based on the well established fact that the organic material supplies the nutrients for the growth of the decomposers. Therefore, the rate of decomposition of an organic material is closely linked with the growth of the organisms responsible for its decomposition. Any increase in the growth rate of the decomposers causes higher rate of decay of that material which supplies the nutrients. By the same rule, any factor inhibiting the growth of the decomposers, such as sub–optimal environmental conditions of temperature, moisture, aeration, and so on, reduces the rate of decomposition.

In the model, organic matter **R** is subject to decomposition. **R** is a mixture of substances (some of them contain nitrogen and others do not contain nitrogen). According to the assumption, loss of carbon from organic matter (plant, animal, residues, or humic matter) or microbial is proportional to the growth rate and the maintenance requirements of the organisms decomposing it (Parnas, 1975),

$$\frac{dC}{dt} = -\alpha \cdot G \cdot B \tag{2}$$

where C is the amount of carbon per unit soil(weight or area) of **R**, t is time, α is thus the total carbon used by the organisms per unit biomass increment. B is the biomass of the decomposers per unit soil. G is the growth rate of the decomposers. It is a function of both carbon and nitrogen. The mathematical expression is given by Michaelis–Menten Kinetics for the bisubstrate reactions (Parnas, 1975)

$$G \propto G_{\max}, \tag{3}$$

where $G_{\max}$ is maximal growth rate under given environmental conditions for a given type of **R** *when* C *and* N *are high so that* $\partial G / \partial C$ *and* $\partial G / \partial N = 0$. $G_{\max}$ *is the parameter affected by* the environmental conditions, it can be corrected for environmental coefficients in any mathematical way. In any case $G_{\max}$ will be higher for a given **R** if the conditions are appropriate for microbial growth and will decrease and might reach zero if the conditions are inappropriate.

4. CH_4 *Production Process*

The major pathways of CH_4 production in flooded soils are the reduction of CO_2 with H_2, with fatty acids or alcohols as hydrogen donor, and the transmethylation of acetic acid or methyl alcohol by CH_4 producing bacteria (Takai 1970; Conrad 1989). According to CH_4 production process described above, the rate of CH_4 production $P(\mathrm{gm^{-2}d^{-1}})$ can be expressed as:

$$P = O_{CH_4} \cdot f, \tag{4}$$

where O_{CH_4} is the amount of total organic carbon used by CH_4 producing bacteria each day $(\mathrm{gm^{-2}d^{-1}})$, f is the efficiency of organic carbon converted into CH_4.

Using assumption 4,

$$f = k \cdot m \cdot e^{-E/RT}, \tag{5}$$

here k is empirical constant, m is irrigation control function. E is activation energy(KJ / mol), R is gas constant, T is soil temperature (K).

According to assumption 2, there are two kinds of organic matter which are applied into soil. One of them is returned by natural, including root stubs, flower falling, deblade and root secretion and exutive root, the other is applied organic fertilizers. And Experiments with C^{14}–labelled substrates (Cappenbery, 1975) showed that the $C^{14}O_2 / C^{14}H_4$ ratio of acetate conversion by a split into CO_2 and CH_4 was 4.378, that is 4.378 moles of CO_2 and 1 mole of CH_4 was produced per mole of organic acid, and the $C^{14}O_2 / C^{14}H_4$ ratio of subsequent reduction of CO_2 to CH_4 was 6.43. Thus the amount of total organic carbon (O_{CH_4}) used by methane producing bacteria is related to the daily total organic carbon (TOM) by the following equations:

$$O_{CH_4} = TOM \cdot \frac{1}{5.378} + TOM \cdot \frac{4.378}{5.378} \cdot \frac{1}{6.43}, \tag{6}$$

$$TOM = O_s \cdot \beta + \sum_{i=1}^{n} O_{mi} \alpha_i + O_r, \tag{7}$$

where O_s is organic carbon content of soil organic matter $(\mathrm{gm^{-2}})$, β is decomposition coefficient for one year, O_{mi} is organic matter content of its organic fertilizers $(\mathrm{gm^{-2}})$, α_i is humidified coefficients of i its organic matter. O_r is organic carbon content of flow–out substrate from rice root and decayed root (gm^{-2}). Humidified coefficients of several organic matter are given in Table 1(Li, 1992).

Table 1. Humidified Coefficients of Some Organic Matters

Organic matter	Measuring points	Minimum value	Maximum value	Average value
Rice straw	16	0.16	0.38	0.23
Wheat straw	15	0.19	0.65	0.27
Rice–wheat root	4	0.32	0.86	0.56
Rape straw	6	0.32	0.43	0.37
Rape cake	6	0.18	0.26	0.27
Chinese milk vetch	7	0.18	0.32	0.24
Pig dung	15	0.30	0.66	0.40
Ox dung	3	0.53	0.77	0.60

Humidified coefficients were respectively measured at flooded fields in Guangzhou, Wuxi, Tianjing and Gongzhuling in China.

Zhu(1985) showed that organic matter accumulation and decomposition in flooded fields for one year were related to yearly applying amount of organic matter, decomposition efficiency and lasting years (n). Since soil nutrient keeps balance for long term, if $n=\infty$, then

Decomposition of soil organic matter for one year
= Amount of organic matter applied for one year

Therefore,

$$TOM = \sum_{i=1}^{n} O_{mi} \cdot \alpha_i + O_r . \tag{8}$$

The soil redox condition is a key component of methanogenesis and methane oxidation. It is governed by oxygen input and consumption in various soil layers. The processes are extremely dynamic with large diurnal fluctuations. Oxygen input is related to water status, algal activity, and diffusion at the soil–water interface and transmission of oxygen through plant aerenchyma tissue to the plant roots. Oxygen consumption will be dependent principally on the incorporation of organic materials and in later stages on algal and dead root biomass. With above reasons, the model assumes that soil redox condition is often satisfied for methane production after rice transplanting.

5. CH_4 *Transport Processes*

There are three processes of CH_4 releasing into the atmosphere from rice paddies. CH_4 loss by air bubbles from paddy soils is a common and significant mechanism. Bubble formation in the soil and the ability of the bubble to pass through the aerobic layers to be emitted are processes requiring applications of soil physics. It is readily observed that the bulk density of soil, which changes during rice growth, influences ebullition to a large extent. Soil texture, mineralogy and tillage parameters or modifiers are all needed to simulate bubble evolution. Diffusion loss of CH_4 across the water surface is another process. Gas diffusion processes are better understood than the formation of bubbles. As a first estimate of evolution from the soil, it is desirable to assume that diffusion gases will be all reoxidized in the surface layer. The third, CH_4 transport through rice plants, which has been reported(Seiler et al., 1984; Cicerone et al., 1983; Minami and Yagi, 1988; Nouchi et al., 1990), as the most important process. CH_4 emission from rice plants is closely related to the amount of soil liquid extracted by root.

Considering the complex mechanisms of bubble formation and floating and the assumption mentioned above that diffusion gases will be all reoxidized in the surface layer, it is simple to compute CH_4 emission from plant and the reoxidized amount of CH_4 in soil. Therefore, methane emission rate F is

$$F = F_1 + F_2, \tag{9}$$

where F_1 is CH_4 emission rate through rice plant, and

$$F_2 = P - P_r - P_o$$

in which P is methane production rate in soil ($gm^{-2}d^{-1}$), P_r is the rate of methane extracted by rice root ($gm^{-2}d^{-1}$), P_o is the rate of methane oxidized in oxic layer. Methane extracted by rice root is related to the rate of root soil–liquid extraction and the capacity of rice plant aerenchyma. And simulation of CH_4 oxidized process is made in the model, using the theory of gas–liquid reaction dynamics by adding a reaction term to diffusion equation.

III. MODEL PROGRAM

The methane model is programmed in FORTRAN77, and consists of a main program and several subroutines to input weather data, initial data, and to compute rice growth, methane production, transportation and emission day by day(see Figure 1). From field experiments it is apparent that methane emissions from rice fields are affected by many factors. The factors clearly identified by field experiments are:

- water level and its history in the growing season
- soil temperature
- fertilizer application
- soil type
- cultivation
- agricultural practice such as seeding or planting

At present there are insufficient data to incorporate all of these factors, and only the effects of water management regime, temperature, organic fertilizer can be included in methane model. Water level and its history in the growing season and some agricultural practices are simulated in rice growth segment of the model. Soil is divided into four layers, among which the top three soil layers are root–bearing layers. The moisture content of root–bearing layers is reduced by root water extraction. Water flow from adjacent soil layers also can cause net increase or decrease in each layer's moisture content. The surface soil layer can lose moisture by evaporation and gain moisture from rainfall and irrigation. If the calculated moisture content of the surface soil layer exceeds saturation, it is assumed that the surface layer is at saturation and the excess moisture is ponded on the surface.

Experiments show that temperature is a sensitive factor for methane production process(Sass et al., 1991; Schutz et al., 1989; Shangguan et al., 1993b). It is important to accurately estimate soil temperature from daily air temperatures. The model utilizes the first two harmonics of the Fourier series and the relationships between the daily maximum and minimum air temperatures. Inputs needed for the model are (i) daily maximum and minimum air temperatures, (ii) thermal diffusivity, and (iii) volumetric heat capacity.

Decomposition of organic fertilizer is simulated in the model. The rate of microbial decomposition of organic material such as plant or animal residues is calculated by a mathematical method provided by Parnas(1975). The relationship between chemical fertilizer and methane emissions is not very clear now.

Soil type is a complex factor. Here soil organic matter content and soil PH are consideredin the model. Other factors will be studied in the future.

Basic data inputs based on the calculating method are:

Climate Data(daily):

Solar radiation and cloud amount

Rainfall Maximum, minimum temperatures

Site and Daily Cultivation Data:

Location(latitude, longitude)

Soil data(organic carbon content, PH)

Irrigation water amounts

Planting data(cultivated areas, transplanted date, growth period)

In addition it requires:

Crop residue and its C:N ratio

Organic fertilizer application(timing and amount)

Floodwater parameters(depth of floodwater and date when flooded)

IV. RESULTS

This section compares model simulated results with experimental field research results. The field experiments of methane emission were conducted in 1988 in Hangzhou and 1992 in Hunan, respectively. The main results and conclusions of the model agree very well with the long known and established experimental results.

The growth curves shown in Figure 2 were produced using weather data in Shanghai, China in 1988. They agree reasonably well with field measurements (Wu et al., 1990).

Figure 3 and Figure 4 show that the seasonal pattern of methane emission rates from rice paddies for early rice is different from that of late rice. Methane emission normally shows three maxim during early rice growth period, while it appears highest shortly after rice is transplanted, and then decreases gradually during late rice growing season. The deviation of seasonal average methane emission rate between modeling value and experiment data is about 10%. For early rice, the modeling value of methane emission rate is 6.19 mg $\cdot$ $m^{-2}h^{-1}$ in Hangzhou in 1988, and that of experimental is 6.43mg $\cdot$ $m^{-2}h^{-1}$. For late rice, modeling value is 18.25 mg $\cdot$ $m^{-2}h^{-1}$ and experimental value is 17.42 mg $\cdot$ $m^{-2}h^{-1}$.

In the whole rice growth period, the seasonal variation of plant transport ability of model output is similar to that of experimental data(Fig.5). It increases with time and reaches maximum during mid-heading time. The transport ability of rice plant is closely related to the uptake of soil liquid by roots, aerenchyma of rice bodies and exchanging ability between leaf blade or leaf sheath and atmosphere. For early and late rice, methane emitted through rice plant accounts for 86% and 47% of the total flux, respectively. These agree well with experimental data, 73% and 55%, respectively.

Figure 6 shows that additions of organic matter to flooded rice soils may enhance methane production and emissions to the atmosphere. Methane flux rates will double with 0.2 gm^{-2} rice straw since methane generation is the terminal step in anaerobic microbial decomposition of organic matter. With suitable soil conditions such as soil temperature and soil redox potential(Eh), the more soil organic matter content, the more methane production and emissions to the atmosphere. The decomposition rate of organic matter, which is insensitive to weather parameters, has a stable decrease rate for long time. The effects of soil organic matter content on methane production and emission appear in their total season average value, while the temporal variation pattern depends mainly on temperature variation and transport processes.

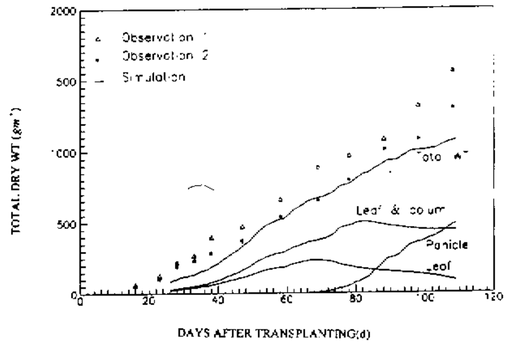

Fig. 2. Observation and simulation of total dry weight of rice plant (Shanghai, 1988).

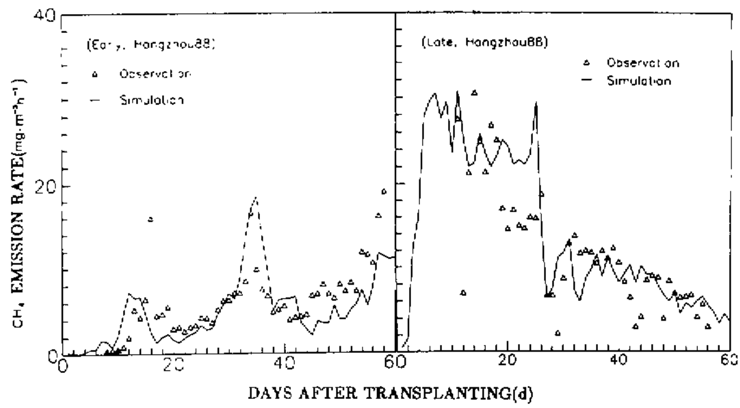

Fig. 3. Experiment and simulation of methane emission from rice fields in Hangzhou in 1988.

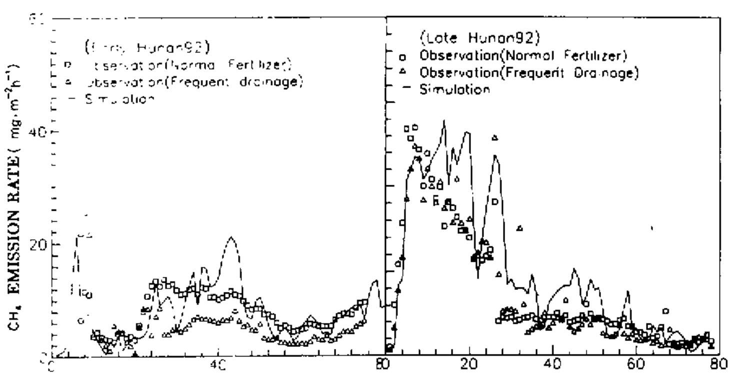

Fig.4. Experiment and simulation of methane emission from rice fields in Hunan in 1992.

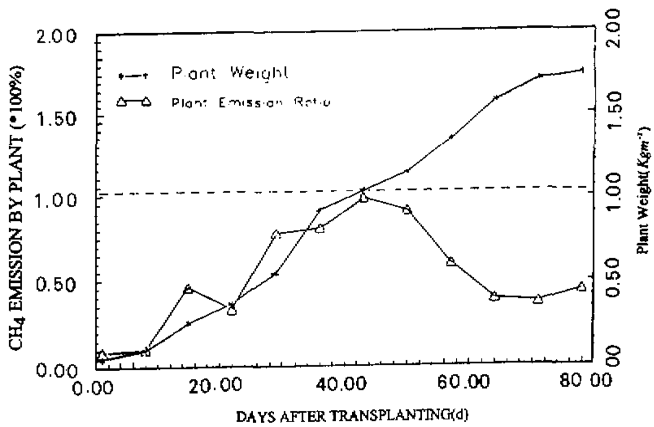

Fig.5. Emission by plant.

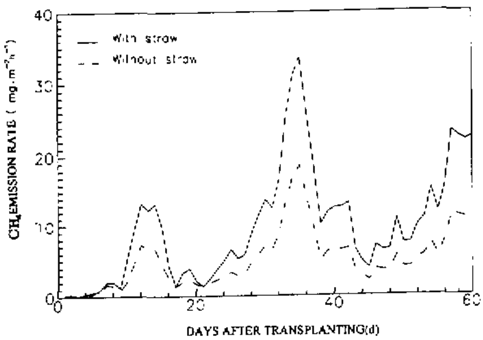

Fig.6. Effects of soil organic carbon content on CH_4 emission.

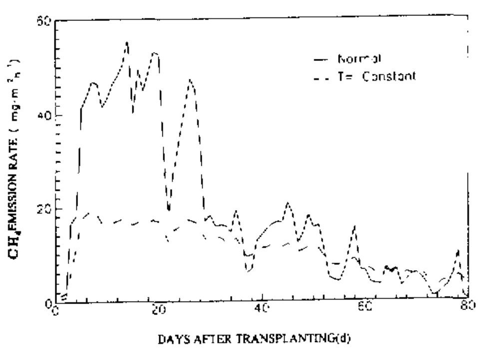

Fig. 7. Sensitive experiment of CH_4 model.

A sensitivity analysis of the model is made by examining responses of simulated methane emission rate to daily mean temperature, solar radiation, rainfall and transpiration, under constant conditions of those environments over the entire growth season(Fig. 7). It is shown that if daily temperature is set at 25°C and other weather parameters vary with time, and the seasonal variation of methane emission changes slightly with time.

V. CONCLUSIONS

The model embodies the effects of climate conditions, fertilizer application and field management on methane emissions. The seasonal variation of methane emission of the model output agrees well with that of field experiments. The deviation of seasonal average methane emission rate between modeled value and experiment data is about 10%. In the whole rice growing period, the seasonal variation of plant transport ability of model output is similar to that of experimental data. Soil organic matter content and soil physics and chemistry are the major factors that determine methane average emission rate, while the soil temperature controls the temporal variation of methane emission from rice fields. It has been shown that the model can satisfactorily explain the spacial variability of CH_4 emission in Hangzhou and Hunan based on the respective climate and rice cultivation technology(i.e., fertilizer applications, soil, water, etc.), and that it also explains the seasonal variation of methane emissions during the rice growing season. However, the model, operating on a daily time step, could not fully simulate potential interactions among fertilizer supply, plant growth, soil moisture, and decomposition. Other direct effects of Eh and fertilizer on methane productions and emissions need to be further investigated and could potentially be included in further versions of the model.

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