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Biosphere–atmosphere exchange of methane in India as influenced by multiple environmental changes during 1901–2010

Kamaljit Banger, Hanqin Tian*, Bowen Zhang, Chaoqun Lu, Wei Ren, Bo Tao

International Center for Climate and Global Change Research, Auburn University, Auburn, AL 36849, USA

HIGHLIGHTS

- Total CH_4 emission increased by ~2.1 Tg C year^{-1} during 1901–2010.
- LCLUC has increased CH_4 emissions by 2.3 Tg C year^{-1}.
- Elevated CO_2 concentration stimulated 0.7 Tg C year^{-1} CH_4 emissions.

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ABSTRACT

It is highly uncertain on how human and natural environmental factors have altered methane (CH_4) emissions from terrestrial ecosystems in India. Using a process-based, Dynamic Land Ecosystem Model (DLEM) driven by climate, land cover and land use change (LCLUC), atmospheric nitrogen deposition (NDEP), atmospheric carbon dioxide (CO_2) concentration, and tropospheric ozone (O_3) pollution, we examined CH_4 flux from terrestrial in India during 1901–2010. The DLEM simulations have shown that total CH_4 flux over the country ranged from 2.9 Tg C year^{-1} to 6.5 Tg C year^{-1} with significant interannual variations driven by climate during 1901–2010. Contemporary CH_4 emissions have primarily occurred from rice fields (3.9 ± 0.9 Tg C year^{-1}) while wetlands contributed to 2.1 ± 0.6 Tg C year^{-1} in the 2000s. During 1901–2010, total CH_4 emission from the terrestrial biosphere has increased by ~2.1 Tg C year^{-1}. LCLUC has increased CH_4 emissions by 2.3 Tg C year^{-1} primarily due to increase in the rice-based cropping systems as well as irrigation expansion during the study period. Elevated CO_2 concentration stimulated plant biomass production in both rice fields and wetlands that increased CH_4 emissions by 0.7 Tg C year^{-1}. On the contrary, climate change decreased net CH_4 emissions by ~1.2 Tg C year^{-1} due to negative effects of extreme high temperature as well as occurrences of extreme drought events on plant growth. Our study suggests that LCLUC and elevated CO_2 concentration have significantly increased CH_4 emissions from terrestrial ecosystems in India.

1. Introduction

Methane (CH_4) is an important greenhouse gas that has 34-folds higher warming potential as compared to carbon dioxide and contributes to approximately 18% of the total greenhouse effect (Montzka et al., 2011; IPCC, 2013). In terrestrial ecosystems, CH_4 is produced by the obligate anaerobes known as methanogens, a part of which is oxidized under aerobic conditions by another group of microbes known as Methanotrophs (Conrad, 1996; Schutz et al., 1989; Bosse and Frenzel, 1997). Due to the prevalence of waterlogged and anoxic conditions, rice fields and wetlands act as primary CH_4 sources while upland ecosystems where soils are not saturated are generally net CH_4 sinks (Bousquet et al., 2006; Khalil and Butenhoff, 2008). At global scale, atmospheric CH_4 concentration has increased from 700 ppb to 1780 ppb since Industrial revolution which is primarily driven by due to fossil fuel burning, livestock breeding, and rice cultivation (Dlugokencky et al., 2003). Recently, the growth rate of atmospheric CH_4 concentration has slowed down in the 1990s, which possibly resulted from decreased microbial sources in Asia (Kai et al., 2011). However, atmospheric CH_4 concentration has started rising again around the beginning of 2007 (Rigby et al., 2008; Heimann, 2011), which necessitates accurate estimation of CH_4 budget at regional and global scales.

* Corresponding author.
E-mail address: tianhan@auburn.edu (H. Tian).

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India has 43 million ha under rice fields, which constitutes approximately 26–30% of the global rice area (Sharma et al., 1995; FAOSTAT, 2014; DES, 2010). A recent remote sensing based study reported that total wetland area was 8.3 million ha distributed primarily on the riverbanks as well as in the coastal areas, which contributes significantly to national CH_4 budget (Garg et al., 1998). Several studies have estimated CH_4 budget in China (Cai et al., 2000; Chen et al., 2013a; Khalil et al., 1993) but only few efforts have been made in India (Sharma et al., 2011; Garg et al., 2006). At national scale, rice fields contribute approximately 3–4 Tg C $year^{-1}$ (Garg et al., 2006; Sharma et al., 2011). In the coastal wetlands, Purvaja and Ramesh (2001) reported CH_4 emissions in the range of 0.9–6.7 Tg C $year^{-1}$. It has been suggested that the estimation of CH_4 budgets based on the emission factors may ignore spatial variations varied impacts of environmental factors, thereby introducing large uncertainties (Kai et al., 2011; Ren et al., 2012). For example, elevated CO_2 concentration stimulates plant biomass production and provides more carbon substrates resulting in higher CH_4 emissions in rice fields and wetlands (Ziska et al., 1998; Baker et al., 2003). Nitrogen fertilizer usage and atmospheric nitrogen deposition (NDEP) may either stimulate or inhibit CH_4 flux in uplands and wetlands (Banger et al., 2012; Aronson and Helliker, 2010). Therefore, regional scale estimation on how multiple environmental changes have altered CH_4 emissions is urgently needed to arrive at a total CH_4 budget at national scale in India.

In this study, we used the process-based Dynamic Land Ecosystem Model (DLEM; Tian et al., 2010) to quantify the contribution of multiple environmental factors (LCLUC, climate, elevated atmospheric CO_2 concentration, NDEP, and tropospheric O_3 pollution) to CH_4 fluxes at 5-arc minute resolution in India during 1901–2010. Specific objectives were to 1) estimate the magnitude and spatial and temporal patterns of terrestrial CH_4 fluxes and 2) to attribute the relative contribution of different environmental factors to dynamics of terrestrial CH_4 fluxes in India during 1901–2010.

2. Materials and methods

2.1. Study area

India is located between 8 and 38° N latitudes and 66–100° E longitudes, covering a geographical area of approximately 328 million ha. There are four distinct seasons in India including: (i) winter (December–February), (ii) summer (March–June), (iii) south-west monsoon season (June–September), and (iv) post-monsoon season (October–November) (Prasad et al., 2007). Four months period of south-west monsoon season accounts for approximately 80% of the annual rainfall in the country. In general, agriculture is the dominant land use type (140 million ha) followed by forests (68 million ha) and wastelands (38 million ha) (DES, 2010).

2.2. Dynamic Land Ecosystem Model

The DLEM is a highly integrated, process-based model that simulates daily carbon, water, and nitrogen as affected by multiple environmental factors including climate, atmospheric compositions (CO_2 concentration, tropospheric O_3), NDEP, LCLUC as well as crop management (harvest, rotation, fertilization, irrigation, etc.). The DLEM operates at a daily time step and at varied spatial resolutions, from meters to kilometers, from regional to global. The detailed information for the DLEM has been well described in our previous publications (Ren et al., 2011; Tian et al., 2011).

2.3. The CH_4 module

The CH_4 exchanges between ecosystems and the atmosphere are a combination of CH_4 production, oxidation, and transport from soil pore water to the atmosphere. The DLEM only considers CH_4 production from dissolved organic carbon (DOC), which is indirectly controlled by environmental factors including soil pH, temperature and soil moisture content. CH_4 oxidation during CH_4 transport to the atmosphere, CH_4 oxidation in the soil pore water, and atmospheric CH_4 oxidation on the soil surface, is determined by CH_4 concentrations in the air or soil pore water, as well as soil moisture, pH, and temperature. Most CH_4-related biogeochemical reactions in the DLEM are described by using the Michaelis–Menten equation with two coefficients: maximum reaction rate and half saturation coefficient. Three pathways for CH_4 transport from soil to the atmosphere include ebullition, diffusion, and plant-mediated transport. It is assumed that CH_4-related biogeochemical processes only occur in the top 50 cm of soil profile. The net CH_4 flux between the atmosphere and soil is determined by the following equation:

$$F_{CH4} = F_P + F_D + F_E - F_{air,\ oxidation} - F_{trans,\ oxidation}$$

where F_{CH4} is the flux of CH_4 between soil and the atmosphere (g C m^{-2} d^{-1}); F_P is plant-mediated transport from soil pore water to the atmosphere (g C m^{-2} d^{-1}); F_D is the diffusive flux of CH_4 from water surface to the atmosphere (g C m^{-2} d^{-1}); F_E is the ebullitive CH_4 emission to the atmosphere; $F_{air,\ oxidation}$ is the rate of atmospheric methane oxidation (g C m^{-2} d^{-1}); $F_{trans,\ oxidation}$ is the oxidized CH_4 during plant-mediated transport (g C m^{-2} d^{-1}). The detailed assumptions and processes are described in our previous publications (Tian et al., 2010; Xu et al., 2010).

2.4. Input datasets

The DLEM needs five types of datasets including: (1) daily climate condition including average, maximum, and minimum temperature, precipitation, shortwave solar radiation, and relative humidity; (2) LCLUC datasets including dynamic crop distribution maps; (3) topography and soil properties (including elevation, slope and aspect; pH, bulk density, and soil texture represented as the percentage of sand, silt, and clay); (4) atmospheric chemistry (e.g. tropospheric O_3, atmospheric CO_2 concentration, and NDEP), and (5) cropland management practices (including nitrogen fertilizer usage, irrigation). In India, significantly uncertainties exist in the LCLUC datasets (Banger et al., 2013), and therefore we generated new datasets. To generate the LCLUC datasets at 5-arc minute resolution, we incorporated high-resolution remote sensing datasets from Resourcesat-1 with historical archives at district ($N = 590$) and state ($N = 30$) levels in India (Tian et al., 2014). For generating the annual irrigation, we calibrated the contemporary irrigation data in the grid format from FAO (AQUASTAT) with inventory records at district, state, and country level from the Ministry of Water Resources (http://wrmin.nic.in/) during 1901–2010. The nitrogen fertilizer datasets were derived from fertilizer inventories at the Department of Economics and Statistics, Government of India (DES, 2010).

The climate data were obtained from CRUNCEP at 0.5 × 0.5° resolution (Viovy and Ciais, 2009) and were re-gridded to 5-arc minute resolution using linear interpolation in ArcGIS. During the study period, mean annual precipitation showed significant interannual variations; however no significant trend ($p > 0.2$) was observed (Banger et al., 2015a,b). On the other hand, mean annual temperature has shown an increasing trend during the study period (slope: 0.03 °C $year^{-1}$; $p < 0.001$). The atmospheric CO_2 concentration data was derived from Carbon Dioxide Information