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Remotely sensed MODIS wetland components for assessing the variability of methane emissions in Indian tropical/subtropical wetlands

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A B S T R A C T

Temperature and area fluctuations in wetlands greatly influence its various physico-chemical characteristics, nutrients dynamic, rates of biomass generation and decomposition, floral and faunal composition which in turn influence methane (CH_4) emission rates. In view of this, the present study attempts to up-scale point CH_4 flux from the wetlands of Uttar Pradesh (UP) by modifying two-factor empirical process based CH_4 emission model for tropical wetlands by incorporating MODIS derived wetland components *viz*. wetland areal extent and corresponding temperature factors (F_t). This study further focuses on the utility of remotely sensed temperature response of CH_4 emission in terms of F_t. F_t is generated using MODIS land surface temperature products and provides an important semi-empirical input for up-scaling CH_4 emissions in wetlands. Results reveal that annual mean F_t values for UP wetlands vary from 0.69 (2010–2011) to 0.71(2011–2012). The total estimated area-wise CH_4 emissions from the wetlands of UP varies from 66.47 Gg $yr^{-1}$with wetland areal extent and F_t value of 2564.04 km^2 and 0.69 respectively in 2010–2011 to 88.39 Gg $yr^{-1}$with wetland areal extent and F_t value of 2720.16 km^2 and 0.71 respectively in 2011–2012. Temporal analysis of estimated CH_4 emissions showed that in monsoon season estimated CH_4 emissions are more sensitive to wetland areal extent while in summer season sensitivity of estimated CH_4 emissions is chiefly controlled by augmented methanogenic activities at high wetland surface temperatures.

1. Introduction

Wetlands described as *"ecological supermarket"* (Mitsch and Gosselink, 2007) are gaining added importance among the scientific community due to their role in assessing greenhouse gas (GHG) emissions particularly methane (CH_4). Methane (CH_4) with 28 times higher global warming potential than CO_2 (Myhre et al., 2013) and higher volume of emissions than any other gas except CO_2 is one of the most important GHG. Wetlands, largest natural emitter of CH_4, contribute about 177–284 Tg of CH_4 per year globally and are the main driver of global inter-annual variability of CH_4 emissions (Ciais et al., 2013). Consequently, changing CH_4 emissions in wetlands can impose vital implications for predicting and understanding the past and future patterns of GHG concentrations and the associated radiative forcing of Earth (Christensen et al., 2003).

Wetland features mainly temperature and areal extent play a decisive role in regulating the CH_4 emissions from wetlands. Wetland areal extent encompassing open water, aquatic vegetation and surrounding hydric soils exhibit wide fluctuations over time which in turn has an immense impact on CH_4 emissions. Thus, accurate and updated estimation of wetland areal extent is mandatory to develop consistent and accurate CH_4 emission coefficients for wetlands. Being an indispensable source of multi-temporal and spatial measures of land surface (Chen at el., 2014), remote sensing (RS) can generate the huge data pertaining to spatial and temporal distribution of wetlands over inaccessible and large areas. Numbers of studies have been done worldwide to evaluate the spatio- temporal distribution of wetlands (Pflugmacher et al., 2007; SAC, 2011; Chen et al., 2014; Garg, 2015) deploying various RS data and techniques which can further be used to assess the significance of wetland areal extent in regional and global CH_4 emission studies.

Temperature fluctuations in wetlands chiefly affect the CH_4 emissions by controlling the rate of CH_4 production by methanogens and release *via* wetland surface and vascular plants. The CH_4 emission rates increase with increase in temperature with optimal rates occurring between 25 and 35 °C (Wassmann et al., 1998; Dubey, 2005). Singh et al. (2000) and Bansal et al. (2015a,b) reported that the CH_4 emissions exhibit strong temperature dependence with high CH_4 emissions at high wetland (water and sediment) temperature in summer season as

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compared to monsoon and winter seasons for man-made as well as natural wetlands of Uttar Pradesh, India. Khoiyangbam et al. (2007) also studied CH_4 emissions with respect to temperature variations for urban wetlands of Jhansi, Uttar Pradesh, India and found a positive correlation between the lake temperature and CH_4 emissions. Christensen et al. (2003) observed that a two degree average summer warming over the temperature range where most of the northern wetlands are located, would result in a 45% rise in mean seasonal CH_4 emissions. Accordingly, assessing the functional relationship between CH_4 emissions and temperature is paramount to understand and predict the impact of temperature on CH_4 flux emitted from wetlands. Existing literature indicates that *in-situ* temperature measurements for wetland surfaces are inadequate/not available and are largely geographically restricted due to limited number of weather stations (Schneider and Hook, 2010). This void can be filled to a great extent by remotely sensed land surface temperature (LST) products that can provide temperature measurements for wetlands over inaccessible and large areas as a function of time and space.

One such, RS and Geographic Information System (GIS) derived temperature product (F_t), has shown a great promise in this context. F_t can be defined as the rate of change of CH_4 emissions in response to change in temperature in remotely sensed LST pixels acquired over the same time period and area for which field measurements are made. Thus, F_t can be used as an indicator of temperature response of CH_4 emissions in CH_4 flux upscaling models. However, very few studies (Agarwal and Garg, 2009; Akumu et al., 2010) have reported the usage of F_t as an important input parameter in CH_4 emission modeling studies. Furthermore, various satellite based LST products predominantly including LST products of Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper (ETM+), Advanced Very High Resolution Radiometers (AVHRR), and Moderate Resolution Spectro-radiometer (MODIS) have been utilized in different studies (Schneider and Hook, 2010; Odunuga and Badru, 2015; Riffler et al., 2015) to monitor temperature fluctuations in wetlands which further espouse the use of RS data to compute realistic F_t values.

Globally, vast tracts of freshwater tropical/subtropical wetlands with large stocks of organic carbon at warmer temperatures are expected to contribute maximally to CH_4 emissions. India is a tropical/sub-tropical country with great physiographical diverse distribution of wetlands. Hence, holistic CH_4 emission predictions from Indian wetlands by integrating CH_4 field measurements with the modern techniques of RS and GIS can provide a valuable tool to examine the wetland areal extent and temperature dependency of CH_4 emissions in natural tropical/subtropical wetlands. However, comprehensive studies reflecting the critique of wetland areal extent and wetland surface temperature in controlling CH_4 emissions from wetlands in spatial domain are very few (Agarwal and Garg, 2009; Akumu et al., 2010). In this regard an attempt has been made in the present research to up-scale, and assesses the sensitivity of up-scaled CH_4 emissions as a function of remotely sensed wetland areal extent, wetland surface temperature and corresponding F_t values in freshwater tropical/subtropical wetlands of Uttar Pradesh (UP), India using MODIS data.

2. Materials and methods

2.1. Study area

Present research work was carried out for the state of Uttar Pradesh (UP) located between 23° 45′–30° 30′ N latitudes and 77°–84° 45′ E longitudes which lies in the high wetland density tropical zone of India (Fig. 1). UP with a total population of 166.2 million, is the most populated state of India covering an area of approximately 2, 40, 928 km^2 (SAC, 2011). Three local wetland sites of UP including Keetham lake, Nawabganj lake and Okhla reservoir were selected for field data collection and analysis. Keetham lake is a deep flowing freshwater pentagonal lake located inside the Soor Sarovar Bird Sanctuary near Agra, while Nawabganj lake is a shallow static marshy/swampy freshwater lake lying in Nawabganj Bird Sanctuary of Unnao. Okhla reservoir, a man-made fresh water reservoir located in Okhla Bird Sanctaury, Gautam Budh Nagar, was created after the construction of Okhla Barrage on river Yamuna in May 1990 for the purpose of irrigation and flood control in the surrounding areas (Fig. 1). Detailed description of the study sites can be referred from Bansal et al. (2015a,b).

2.2. CH_4 emission estimation

Total CH_4 emissions from wetlands of UP have been estimated using Eq. (1) developed by modifying the two- factor empirical process based model for tropical wetlands given below (Eq. (2); Liu, 1996; Agarwal and Garg, 2009; Akumu et al., 2010)

$$E_{CH4} = E_{obs}.A.F_t \quad (1)$$

$$E_{CH4} = E_{obs}.f_t.f_w \quad (2)$$

where:

E_{CH4} is the total amount of estimated CH_4 emissions in both the equations.

E_{obs} represents the observed mean CH_4 flux values taken from Barlett and Harris (1993) in Eq. (2) whereas in Eq. (1), E_{obs} is the observed CH_4 flux calculated in field.

f_w is the water availability factor in terms of precipitation/evaporation ratio in Eq. (2) which is replaced by A in Eq. (1). A is the wetland areal extent estimated using MODIS data to represent the effect of water availability factor on CH_4 emissions from wetlands in spatial domain (*i.e*, entire UP).

f_t is the temperature factor similar to that used in Cao et al. (1995) and estimated using field temperature values (T_s in °C) in Eq. (2) which is replaced by F_t in Eq. (1). F_t is the remotely sensed temperature factor estimated using MODIS LST data to take into account the effect of temperature on CH_4 emissions from UP wetlands in spatial context for the same time period when all the field measurements (temperature as well as CH_4 flux) were conducted.

In our study, three prime assumptions/limitations have been considered for developing the Eq. (1) which include: (i) Temperature is assumed to be linearly related with CH_4 emissions, (ii) Coarse spatial resolution of MODIS (1 × 1 km) restrains the scope of the present study to wetlands larger than the minimum mapping unit of MODIS *i.e.*, 900 ha and the incremental MODIS wetland area estimated using AWiFS data, and (iii) Due to unavailability of MODIS data for monsoon season, MODIS data available for the month of October has been used to estimate total CH_4 emissions for monsoon season assuming that monsoon season starts in July and extends up-to October. Methodology used in the present study is detailed in Fig. 2.

2.3. Observed CH_4 flux (E_{obs}) estimation

2.3.1. Point CH_4 flux measurements

To account for variations in CH_4 flux from wetlands depending upon season, time, location (altitude and geographical coordinates), biophysical status of the wetland (water quality, soil conditions, vegetative characteristics *etc.*), and varying environmental conditions (temperature, rainfall, *etc.*) current point CH_4 flux data was generated for UP. Field measurements for CH_4 flux were carried out for three distinct seasons at all three representative wetlands during both the sampling years, *i.e.*, monsoon (July–October), winter (November–February) and summer (March–June).

To consider for heterogeneity of water body and facilitate systematic sample collection, each wetland was divided into three zones, namely, shallow water zone (SWZ: depth < 150 cm for Keetham lake and Nawabganj lake; depth < 200 cm for Okhla reservoir), deep water zone (DWZ: depth ≥ 150 cm in Keetham lake and Nawabganj lake; depth ≥ 200 cm in Okhla reservoir) and the exposed wetland soil zone