



EDDY COVARIANCE TECHNIQUE for Measurement of Mass and Energy Exchange in Lowland Rice

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NICRA
National Innovations in Climate Resilient Agriculture



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PREFACE

Rice is a staple food for more than a half of the world's population. One of the major consequence of rice production is that it produces and emits greenhouse gases (GHG) to the atmosphere. The precise measurements of GHG and various other energy balance components are probably a concern to the scientific fraternity. The eddy covariance technique provides precise measurements over a large homogenous area growing with crops. This atmospheric measurement technique is employed for measurement of CO₂, water vapour, CH₄ and heat flux over crops, pastures, forests, lakes and other water bodies; providing information on net ecosystem carbon dioxide exchange, net ecosystem methane exchange, carbon balance, energy balance of the ecosystem.

This research bulletin covers the eddy covariance data and information generated for the subtropical lowland rice. The bulletin may serve as a guide for establishment of eddy covariance site, data collection, data processing and presentation in a holistic manner.

The authors believe that the findings will be of interest to scientists, students, researchers, academicians, donors, and funding agencies. The authors sincerely acknowledge the financial support provided by the Indian Council of Agricultural Research funded National Innovations in Climate Resilient Agriculture (NICRA) project for conducting experiments on eddy covariance system.

Authors

1. Introduction

Rice is the staple food for about half of the world's population, grown on nearly 161 million ha of land in 100 countries with a total production of 741.5 million tons (Kumar and Ladha 2011). It is the most important crop grown during the rainy season in Asia, especially in the South-East Asia region and India. It is grown in various ecologies and environments including various farming situations such as shallow lowland, semi-deep lowland, deep water lowland, and upland; climatic zones such as tropical, subtropical, and temperate regions, at altitudes ranging from 6 feet below to 2700 feet above mean sea level, in various ecologies such as irrigated, rainfed and flood-prone ecologies (Pathak *et al.* 2018). However, in tropical India, irrigated lowland rice is extensively grown on 14.4 million hectares, accounting for 32.4% of the total rice area (Singh 2009). Lowland rice cultivation practices impoundment of water using bunded fields for at least a considerable part of the growing period. This impoundment of water makes this system a unique anthropogenic manipulator of ecosystem carbon dynamics, water balance, and energy balance in a different way than other arable crops. Rice emits significant amounts of Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), and water vapour. It currently emits about 36 million metric tonnes (18% of total CH_4 emissions in India) of methane and contributes 2.5% to radiative forcing (Kritee *et al.* 2018; Pathak *et al.* 2018). In rice cultivation, N_2O has been estimated to contribute about 25% to the total global greenhouse gas (GHG) on a 100-year basis. Water, a critical input for rice production, is largely lost through evapotranspiration, which contributes to water vapour as a GHG (Hatala *et al.* 2012). Solar radiation is an important parameter that not only determines the productivity and quality of rice but also decides the net energy balance of the ecosystem that controls the microclimate. The solar radiation use efficiency of rice is 1.02-1.51 g MJ^{-1} (Gautam *et al.* 2019). Real-time measurement based on the eddy covariance system provides a more realistic estimate of the Carbon (C), water, and energy budgets in the rice ecosystem.

In general, measurement of GHGs can be done in two ways : (i) manual gas chamber, (ii) eddy covariance methods. The simplest way of measurement is the manual gas chamber method, where the gas is collected at the experimental site through a chamber made of acrylic plates and the gas samples are then analyzed in a gas chromatograph. The data generated in this way has certain limitations as these data are measured discretely and extrapolated for a whole day. Linear interpolation is used between two observations. Therefore, this method is associated with errors in the measurement. In contrast, the eddy covariance method (EC) is a fast, sensor-based, real-time measurement of greenhouse gasses and heat fluxes. The EC method has become one of the most popular method for measuring GHGs and energy balances exchange between the rice ecosystem and the atmosphere.

The covariance of GHGs concentration or heat and the vertical wind velocity component (U_z) is considered as a flux (Paw *et al.* 2000). Sensors are placed at an appropriate height above the uniform crop surface. High frequency (10-Hz) data are recorded in the data

logger. Assuming perfect turbulent mixing, all the high-frequency data are cumulated over a half-hourly basis to calculate C, water, and heat balances from daily to annual time scales.

2. Eddy covariance, various sensors, and their function

The EC system is an micrometeorological measurement technique for measuring vertical turbulent fluxes of energy components and GHGs concentration within atmospheric boundary layers. It is a combination of different sensors (Figure 1) that measure GHGs concentration, energy, and momentum, which are converted to fluxes by covariance with vertical wind speed.

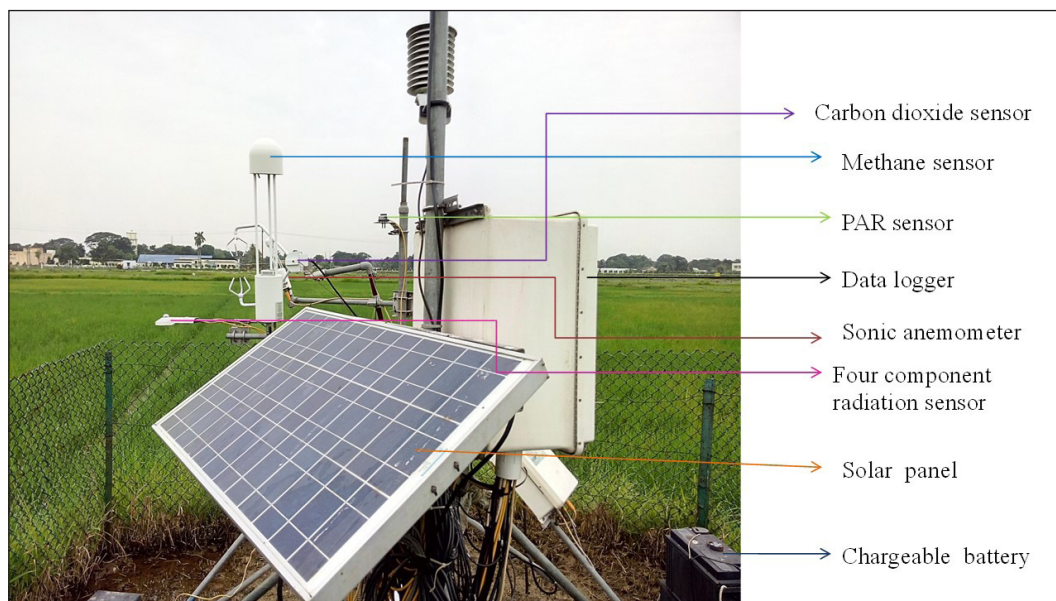


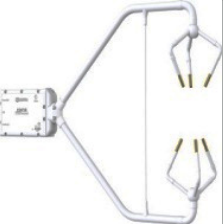
Figure 1: Labeled open path eddy covariance system

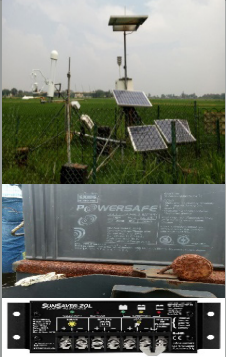
There are two types of EC systems: (i) open path and (ii) closed path. Open-path systems can be operated at low power and the spectral responses are good, allowing estimates of the instantaneous gas mixing ratio. In contrast, closed-path EC systems are well suited for long-term measurements and require less maintenance. However, flux measurement of a gas (*e.g.*, water vapour) that adheres to the surface of the sensor path requires special flux correction.

Different components of the eddy covariance system include (i) a sonic anemometer to measure wind speed in three-dimension, sonic temperature, and wind direction. The measurement of the sonic anemometer is based on the speed of sound in air transmitted via a transducer. Another transducer collects reflections of the sound. The delay between the transmitted and received time is used for the measurement of wind speed. (ii) an open path infrared gas analyzer (LI-7500A) to measure the fluctuations in CO₂ and water vapour

densities, (iii) an open path infrared methane gas analyzer (LI7700) (iv) A 4-component radiation sensor measuring net radiation (NR), shortwave upwell (SU), shortwave downwell (SD), longwave upwell (LU) and longwave downwell (LD) radiations. Air temperature-relative humidity sensor measures air temperature (T_a) and relative humidity (RH). Photosynthetically active radiation (PAR) is measured using silicon photodiode quantum sensor. The soil temperature probe measures soil temperature (T_g) at 3 depths (5, 15, and 30-cm). Table 1 shows the details of specific sensors, their make, and measurements. All the sensors are installed on a tripod aluminum mast and aligned perpendicularly to the prevailing south-east wind direction. To minimize the interference of raindrops, LI-7500A head is tilted by 15° . All data (10-Hz) are stored in 2GB memory card attached with a data logger (CR3000).

Table 1: Specifications of the sensors of the open eddy covariance system

Sensor	Device	Manufacturer	Measurement variables	Photos
Sonic anemometer	CSAT3	Campbell Scientific	Real-time three-dimensional wind speed, sonic temperature, and wind direction	
Carbon dioxide/ H_2O Analyzer	LI 7500A	LICOR	CO_2 and water vapour fluxes, density and concentration	
Methane Analyzer	LI 7700	LICOR	Methane concentration, density, and flux	
Four component net radiometer	CNR4 net radiometer, Thermopile detector	KIPP & ZONEN	Incoming (SW) and outgoing (LW) solar radiation along with net radiation	

Photosynthetically active radiation sensor (PAR)	Silicon photodiode (LI190SB)	KIPP & ZONEN	Photosynthetically active radiation in solar radiation	
Fine wire thermocouple	FW3	Campbell Scientific	Air temperature	
Relative humidity	Air temperature and relative humidity sensor (HMP45C)	Campbell Scientific	Air temperature (Ta) and Relative humidity (RH)	
Soil temperature probe	107 B	Campbell Scientific	Soil temperature at 5, 15 and 30 cm depths	
Soil heat flux plates	HFT3-L	Campbell Scientific	Soil heat flux	
Micrologger data logger	CR3000	Campbell Scientific	Real-time and fast response integration, recording, and storage of data	
Solar panel and battery with SunSaver	DC Panel	-	Power supply	

3. Practical application

Eddy covariance system measures carbon dioxide, methane, water vapour, sensible heat, latent heat, soil heat fluxes which are used to study carbon balance, gross primary production (GPP), ecosystem respiration (RE), net ecosystem exchange (NEE) of greenhouse gases, hydrological and energy partitioning, water loss, energy balance in the rice ecosystem. This instrument brings a paradigm shift in climate change research as it deals with real-time data of the agro-ecosystem. This system is widely used for validation and fine-tuning of global climate and weather models, ecological models, biogeochemical models, and downscaling of the remote sensing data from satellites and aircraft. Apart from the monitoring of GHGs in agriculture, it has wide use in many industrial monitoring, landfill and environmental management, and monitoring of lakes and other water bodies.

4. Principle of measurements

Airflow is a horizontal flow of several rotating eddies. Each eddy can be explained by its horizontal (u), lateral (v) and vertical (w) velocity component. Principally, the eddy covariance method measures the turbulent flux data by enumerating the covariance of fluctuations in the vertical wind velocity (w) and the physical quantity to be measured. In turbulent flow, vertical flux is presented as (Burba 2013):

$$F = \overline{\rho_a w s} \text{ -----(Eq 1)}$$

Where ρ_a is the density of air and s is the dry mole fraction of the measured gas. Each term can be split into its mean and deviation using Reynolds decomposition:

$$F = \overline{(\bar{\rho}_a + \rho'_a)(\bar{w} + w')(\bar{s} + s')} \text{ -----(Eq 2)}$$

Equation 2 may be expanded as:

$$F = (\bar{\rho}_a \bar{w} \bar{s} + \bar{\rho}_a \bar{w} s' + \bar{\rho}_a w' \bar{s} + \bar{\rho}_a w' s' + \rho'_a \bar{w} \bar{s} + \rho'_a \bar{w} s' + \rho'_a w' \bar{s} + \rho'_a w' s') \text{ -----(Eq 3)}$$

By considering averaged deviation from the average is zero (air density fluctuations assumed negligible ($\rho'_a \bar{w} s', \rho'_a w' \bar{s}, \rho'_a w' s' \sim 0$) and mean vertical velocity assumed negligible for horizontal homogeneous terrain ($\bar{\rho}_a \bar{w} \bar{s} \sim 0$), the equation 3 may be rewritten as:

$$F = \overline{\rho_a w' s'} \text{ -----(Eq 4)}$$

Based on the above principle, the various mass exchange and energy balance parameters are measured. The mean vertical CO₂ flux density (F_{CO_2}) is obtained as a covariance between fluctuations in w (w') and the CO₂ mixing ratio (c_{CO_2}') on a half-hourly basis:

$$F_{CO_2} = \overline{\rho_a w' c_{CO_2}'} \text{ -----(Eq 5)}$$

In the equation, ρ_a refers to the air density, the overbars indicate average over time, and primes indicate the fluctuations about mean.

The mean vertical flux density of CH_4 (F_{CH_4}) is calculated as the 30-minute covariance between w' and the CH_4 mixing ratio (c_{CH_4}') by the following formula:

$$F_{\text{CH}_4} = \overline{\rho_a w' c_{\text{CH}_4}'} \text{-----}(\text{Eq 6})$$

Water vapour flux is calculated by covariance of w' and water vapour concentration:

$$F_{\text{H}_2\text{O}} = \overline{\rho_a w' q'} \text{-----}(\text{Eq 7})$$

Where q' is the fluctuation in specific humidity, ρ_a is dry air density, the overbar denotes the mean value.

Using the eddy covariance principle, the sensible heat flux (H) is derived by the product of the mean air density and the covariance between deviations in vertical wind speed and temperature and converted to energy units by multiplying specific heat.

$$H = \rho_a C_p \overline{w' T'} \text{-----}(\text{Eq 8})$$

Latent heat flux (LE) is measured using an eddy covariance system using the measurement of water vapour and converted to energy units.

$$LE = \lambda \frac{M_w/M_a}{P} \rho_a \overline{w' e'} \text{-----}(\text{Eq 9})$$

In the equations (8 and 9), ρ_a refers to the air density, C_p denotes to specific heat capacity of air at constant pressure, w is vertical wind velocity, T is air temperature, λ is the psychrometric constant, M_w/M_a is the ratio of molecular weight of wet to dry air, e is water vapour pressure, P is air pressure.

5. Installation

The eddy covariance system is to be installed in a flat, homogeneous area representing a similar ecology. The height of the sensor is fixed at a constant flux layer which is 1.5-2 times higher than the surface roughness (Figure 2). Sufficient fetch (100 times of the height of sensor) is to be kept in the dominant wind direction. Uniform variety/crop should be grown followed by uniform management of soil and nutrient. This assures a uniform height of the vegetation and even surface roughness length during the growing season (Burba 2013).

The assumptions for the establishment of the eddy covariance flux tower are:

- Fluxes are measured within the boundary layer of interest.
- The terrain is horizontal and uniform; the mean value of fluctuations is zero; density fluctuations are negligible; convergence and divergence of flow are negligible.
- Measurements should represent an upwind area. Each point measurement corresponds to an upwind area (fetch area).

- The nature of the flux should be completely turbulent and net vertical transfer is made by eddies.
- Instruments should detect minute changes at high frequencies (from 5- 40 Hz).
- Fetch area is adequate and sufficient for measuring the flux (*e.g.*, if the eddy tower is established at 1-m then fetch area is 100-m in the dominant wind direction. Hence the entire 100-m must be covered with the crop of our interest at least in the dominant wind directions).

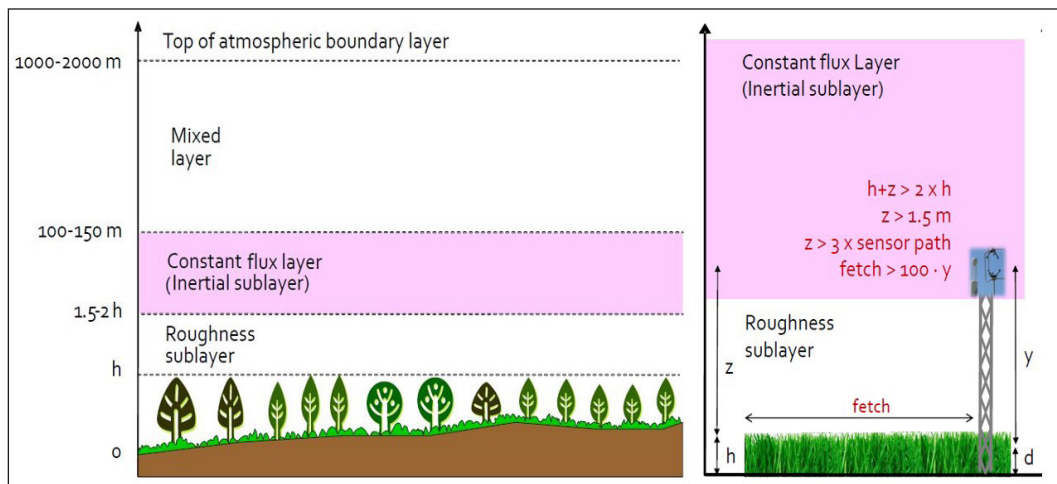


Figure 2: Different atmospheric layers and installation of eddy covariance tower (Burba and Anderson 2010)

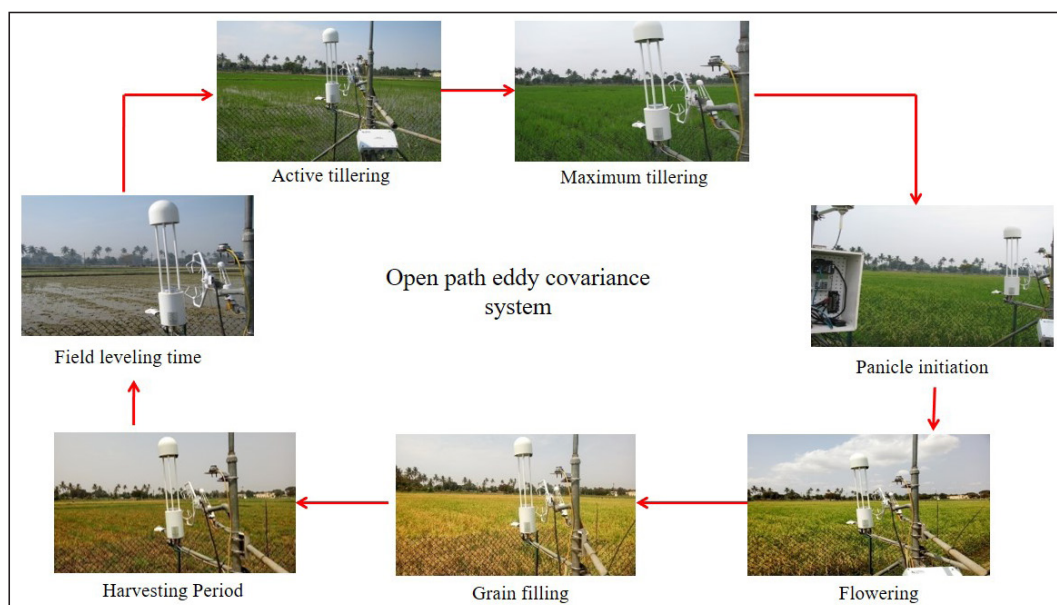


Figure 3: Field measurements of mass and energy fluxes at different stages of crop growth

Eddy covariance (EC) system installation site of National Rice Research Institute (NRRI), is located at 20°26'60.0"N latitude, 85°56'10.9"E longitude on a tripod at C block of experimental research farm of NRRI in the mid of a rice paddy field covering 2.25 ha and sensors are installed at 1.5 m above ground (Chatterjee *et al.* 2019a, 2019b). Sufficient fetch (150 m) is kept in the dominant wind direction which is south and south-east. Lowland rice of 21-25 days age are transplanted with normal spacing. The crop in dry and wet seasons are harvested during May and November, respectively. Standard water management practice is followed to keep average of 5-8 cm standing water throughout the growing seasons which was drained during the last two weeks. Standard package of practices for nutrient management was followed. The eddy covariance data were recorded all the stages of crop growth (Figure 3) and fallows.

6. Processing of real-time raw data

Eddy covariance data are processed using several flux calculation methodologies. Calculation of fluxes includes checking the data for errors or gaps, aligning the data to account for time lags, and calculating fluxes based on the half-hour or one-hour averaging intervals. The eddy covariance system is normally configured through computer software. The software usually provides an option to view the real-time data as a graphical presentation. Campbell Scientific provides LoggerNet software as a comprehensive suite of applications for working with their data loggers. Eddy covariance data are recorded at 10-Hz frequency. The real-time data is stored in TOA3 form (*i.e.* ASCII text form size near about 1.94 GB). Then this raw data is transferred using a Campbell Scientific data logger to collect data from Shape Arrays (SAAs). The output format for data files is stored as ASCII long header table data (TOA5). Further, there are several software programs (*e.g.*, EdiRe, EddyPro, TK3 *etc.*) to process long header binary data (TOB1) of eddy-covariance.

The EC flux data are further processed for various corrections (Mauder and Foken 2011). EdiRe software was used to process TOB1 data and it is reported as 30-min mean data after taking care of the quality control issues (Foken *et al.* 2012; Richardson *et al.* 2012; Mauder *et al.* 2013; Swain *et al.* 2016), which includes 'WPL' correction (Webb *et al.* 1980), frequency response losses (Aubinet *et al.* 1999), time lag (Goulden *et al.* 1996), coordinate rotation (Kaimal and Finnigan 1994), sonic virtual temperature conversion for sensible heat flux (Mauder *et al.* 2006), and spike detection (Vickers and Mahrt 1997). In the spike detection algorithm, values exceeding the mean ± 3 times of the standard deviations is considered as spike (Falge *et al.* 2001; Anderson and Wang 2014). Again, the flux data having lower friction velocity below threshold ($u^* \sim 0.1 \text{ m s}^{-1}$) is removed (Massman and Lee 2002; Li *et al.* 2005). Data gaps are then filled using the mean diurnal average method in a window of 10-days for gaps longer than 3h and using the lookup table method and also by linear interpolation for gaps shorter than 3h (Falge *et al.* 2001). The flow chart for processing of eddy covariance raw data is shown in Figure 4.

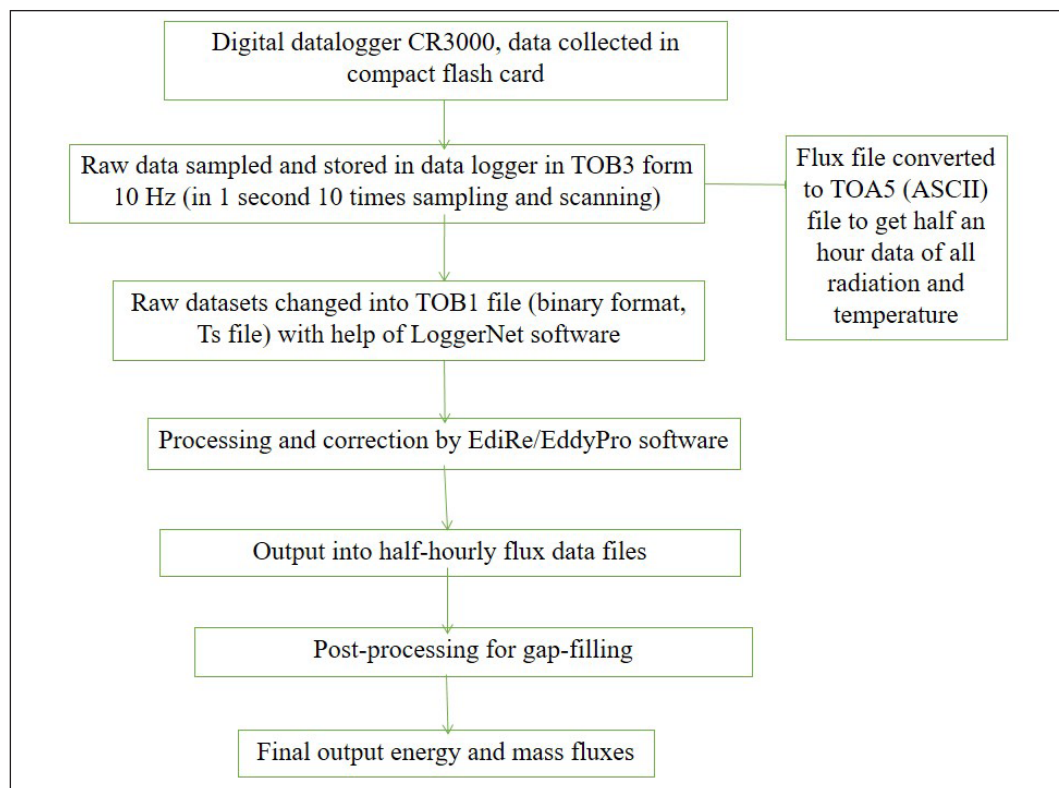


Figure 4: flow chart for processing of eddy covariance raw data

7. Flux correction

Various errors are involved in the measurement due to problem in the instrument, time response, sensor separation, tube attenuation, averaging scalar path, high and low pass filtering, digital sampling, sensor time delay, unlevelled instrumentation, spike and noise, density fluctuation, sonic heat flux error, band-broadening, and data filling. To lessen such error a number of measures can be taken like time lag or time delay, despiking, detrending, planar fit / coordinate rotation, WPL correction, U^* (U-star) etc.

Axis rotation for tilt correction: Sonic anemometer may not be properly levelled or imperfectly mounted on the tripod in the Eddy covariance system. If the 'Z' axis (vertical) of the sonic anemometer is not aligned to the surface, there will be a variation in the flux data, known as tilt errors. The solution to this issue is to fit the sonic anemometer as close as possible to the required orientation. When the fetch area of the tower site is substantially flat and homogeneous, as often found in grassland, a double-rotation method is advocated. This method is also followed when canopy height and roughness length changes very fast, such as during the crop growing season, especially during the vegetative stages. For the sloping topography or dis-homogenous canopy, the planar fit method is followed.

Time lag or time delay: This basically delays in time of recording a data by the sensor and the data logger (Figure 5). The probable reason of time lag is due to the variation in electronic signal and spatial separation between the sonic anemometer and other sensors. Time lag can be determined for each averaging interval by cross-correlation analysis between the parameter of interest and vertical wind component. Compensation of time lags is always to be compensated, except if an open path analyzer is located very close to the sonic anemometer of the eddy covariance system. Sometimes, a constant value for time lag is used while doing the time lag corrections. This value is usually stored in the metadata and the software uses the same value in every operation. However, the use of constant-time lag is advocated when a closed path sensor is used. Even in a closed path sensor, constant time lag should not be used while measuring water vapour flux as water vapour sticks to the path.

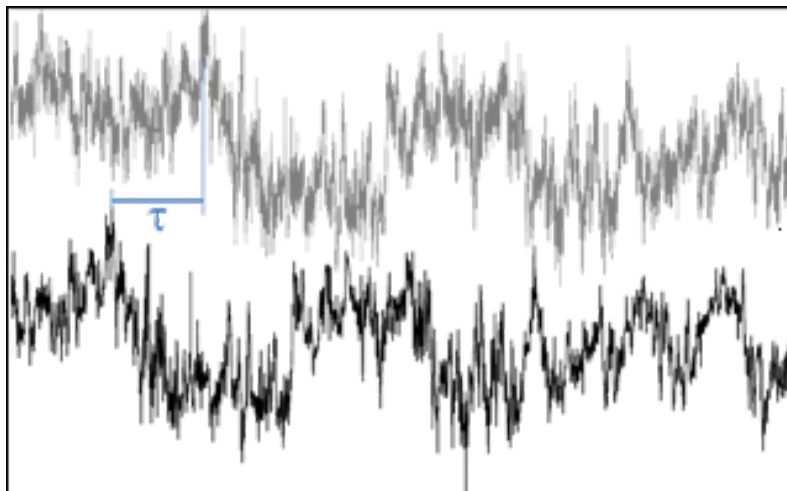


Figure 5: Time lag or time delay

(https://www.licor.com/env/support/EddyPro/images/timelag_with_frame.png)

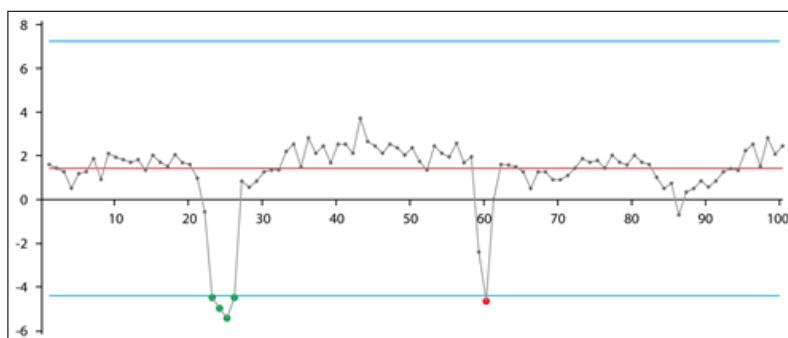


Figure 6: Example of spike detection (green points are not spike, while the red points are spike)

The red and blue lines are window mean and plausibility range, respectively

(<https://www.licor.com/env/support/EddyPro/images/Despiking.png>)

Despiking: Spike means any absurd data (deviated largely from the average nearby data points) which may not be the true representative of the situation. It can be caused by internal instrumental problems or by external influences like bird droppings, dirt, precipitation, cyclone, moving of vehicle or any extreme event *etc.* The despiking procedure involves detection and removal of outlier values in the time series. These techniques are used to correct abnormally large variances, skewness, kurtosis as well as discontinuities, and remove the spikes. In the case of short peaks (measured by deviation from normal data range), the algorithm removes the spike data, and gaps are filled through linear or nonlinear interpolation. In case of a large spike the measurement may be flagged or removed. A spike is identified when there are three consecutive outliers in the data series (Figure 6) with respect to the plausibility range of values of a variable (Vickers and Mahrt 1997). In the process of spike detection, one or two or three consecutive values are considered as a single spike. In EddyPro, a spike is detected in about 20 iterations. In this process, the previous repetition may appear again as a spike due to the change in plausibility range. The plausibility range for spike detection is shown in Table 2.

Table 2. Plausibility range for spike detection

Variable	Plausibility Range
Horizontal wind velocity (U_x , U_y)	$\mu \pm 3.5 \sigma$
Horizontal wind velocity (U_z)	$\mu \pm 5.0 \sigma$
Net ecosystem carbon dioxide exchange (NEE) and Water vapour flux (H_2O)	$\mu \pm 3.5 \sigma$
Net ecosystem methane exchange (NEME)	$\mu \pm 8.0 \sigma$
Temperatures, Pressures	$\mu \pm 3.5 \sigma$

μ , mean of the variable; σ , standard deviation of the variable

(<https://www.licor.com/env/support/EddyPro/topics/despiking-raw-statistical-screening.html>)

Detrending: Detrending and high-pass filtering are basically utilized to reduce random or systematic error in flux estimates caused by low-frequency bias in turbulent time series. The fluctuation in flux measurements occurs due to diurnal (day and night fluxes) and sudden change in concentration, wind speed, and wind direction. Linear, block average, running mean, exponential running mean, time constant methods of detrending are available in most of the eddy covariance software. Use of block average method is most often advocated for detrending. If a long flux averaging interval (one hour and above) is selected, the time constant method of detrending is the best choice.

WPL correction: A Webb–Pearman–Leuning (WPL) correction is required to correct the fluctuations in trace gas concentrations due to the fluctuations in temperature and humidity. While calculating flux, the values of gas density obtained in gas analyzers are to be transformed into mixing ratio (*i.e.*, mass of gas per mass of air) in which the density of air is

used. The density of air varies with fluctuates in temperature and pressure. Such variations are compensated using WPL corrections.

U^* (U -star): During day-time and nighttime eddy turbulence may vary. It is low at night-time as compared to day. U^* or friction velocity is used for spike detection and determined on the basis of lower threshold limit of velocity of air during night-time, below which ecosystem fluxes can be ignored.

8. Eddy covariance-based measurement of mass exchange and energy balance- a case study of lowland rice

Lowland paddy behaves differently in mass and energy exchange as it is cultivated under continuous standing water. Water layer over soil change the soil Eh, store energy, and source of water vapour that completely change the microclimate of the region. In the following sections, we have discussed how mass and energy exchange in a lowland paddy behaves by taking examples of NRRI.

8.1 Mass exchange measurement

Mass exchange measurement in rice field includes measurement of concentrations and fluxes of CO_2 , CH_4 , N_2O and water vapour. Carbon dioxide gas is a part of carbon cycle which is governed by its assimilation in photosynthesis and its release through autotrophic and heterotrophic respiration. This mainly depends on soil organic carbon content, type of crop, leaf area index, plant water supply, and management practices (Reichstein *et al.* 2005; Smith *et al.* 2010). During cropping seasons of lowland rice anaerobic environment prevails in the soil which accumulates organic matter. This accumulated organic matter in soil is oxidized during the fallow period to CO_2 (Maljanen *et al.* 2001). Natural and anthropogenic wetlands (rice paddy) are the largest source of methane accounting for about 20–50% of its emissions globally (Ciais *et al.* 2013). Rice as a sole crop emits 25 MT methane (12% of agricultural contribution) globally and 3.5 MT methane (18% of agricultural contribution) in India (Pathak *et al.* 2018). Although methane is the dominant GHG in the continuously flooded rice field, emission of nitrous oxide is found to be 30–45 times higher in intermittently flooded rice compared to continuous flooding (Kritee *et al.* 2018). Being a semi-aquatic crop, rice paddy consumes a large quantity of water. This water is mostly lost through evapotranspiration, which is controlled by water vapour flux in flooded rice contributing to water vapour as a greenhouse gas (Hatala *et al.* 2012). In the following sections, we will discuss various mass exchange parameters measured in lowland rice paddy.

8.1.1 Net ecosystem carbon dioxide exchange

Carbon dioxide flux (F_{CO_2}) is measured from carbon dioxide exchange between canopy and atmosphere and it is mainly used to measure carbon budgets over agricultural ecosystems. A positive value of F_{CO_2} indicates a transfer of net CO_2 from the canopy to the atmosphere,

while a negative value of F_{CO_2} indicates net CO_2 absorption by the vegetation. The net carbon dioxide flux as measured by F_{CO_2} is also called net ecosystem exchange of CO_2 (NEE) when deals with the agricultural ecosystem. By definition, NEE is the difference between photosynthesis by plant canopy and ecosystem respiration during daytime and ecosystem respiration at night. The importance of net ecosystem carbon dioxide exchange are:

- Measurement of carbon balance
- The NEE data can further be partitioned into gross primary productivity (GPP) and ecosystem respiration (RE).
- The NEE can be used to measure net ecosystem productivity (NEP). The NEE tends to NEP (opposite sign) when fluxes are small due to high atmospheric stability (Chapin *et al.* 2006).

The NEE is governed by several environmental variables such as latent heat flux, vapour pressure deficit, leaf area index, growth stages of rice crop, canopy irradiance, stomatal response, heat stress, high evaporative demand, and biomass (Nair *et al.* 2011). In lowland paddy ecosystem, NEE is highly and significantly correlated ($p < 0.0001$) with PAR, precipitation, air temperature and soil temperature.

8.1.1.1 The seasonal, diurnal and inter-annual variation in NEE

Seasonal variation refers to the variation in NEE obtained during crop growing seasons and fallows in a year. In a year, there are two growing seasons and two fallows *viz.*, dry season (DS) for 1-125 Julian days, dry fallow (DF) for 126-181 Julian days, wet season (WS) for 182-324 Julian days and wet fallow (WF) for 325-365 Julian days. During the cropping seasons, NEE decreases gradually from the vegetative stage to maximum tillering and then slightly increases at flowering to harvesting. The net assimilation during fallow seasons ($-0.065 \text{ mg m}^{-2} \text{ s}^{-1}$ in dry fallow and $-0.012 \text{ mg m}^{-2} \text{ s}^{-1}$ in wet fallow) is attributed to the presence of ratoon of rice and weeds in the field.

Diurnal variation refers to the daily cycle of flux plotted with 48 half-hour data points averaged over a season or a year. This variation showed the variation of NEE during daytime and nighttime. This variation is useful in the partitioning of NEE into GPP and RE. In general, NEE remains negative during the sunshine period with a peak at 11:30 AM -12:30 PM behaving as net CO_2 sink. During the night hours, it acts as a source of CO_2 as it is contributed by respiration. Air temperature, soil temperature, vapour pressure deficit, PAR, water vapour flux and soil moisture content mainly influence the diurnal variation of NEE (Chatterjee *et al.* 2019b).

Inter-annual variations (IAV) of NEE refer to the variation of NEE across years. The IAV infers the uncertainty in the measurement of NEE. In some years, NEE shows a wide variability (*e.g.* 2014-2016), while lower variability in other years (2017-2018) (Figure 6). The main reason for inter-annual variability is mainly due to variation in temperature anomalies.

An example of the seasonal variation of NEE is shown in figure 7. The NEE during dry season, dry fallow, wet season and wet fallow were observed as $0.086 \text{ mg m}^{-2} \text{ s}^{-1}$, $-0.104 \text{ mg m}^{-2} \text{ s}^{-1}$, $-0.110 \text{ mg m}^{-2} \text{ s}^{-1}$, and $-0.099 \text{ mg m}^{-2} \text{ s}^{-1}$, respectively (Chatterjee *et al.* 2019b).

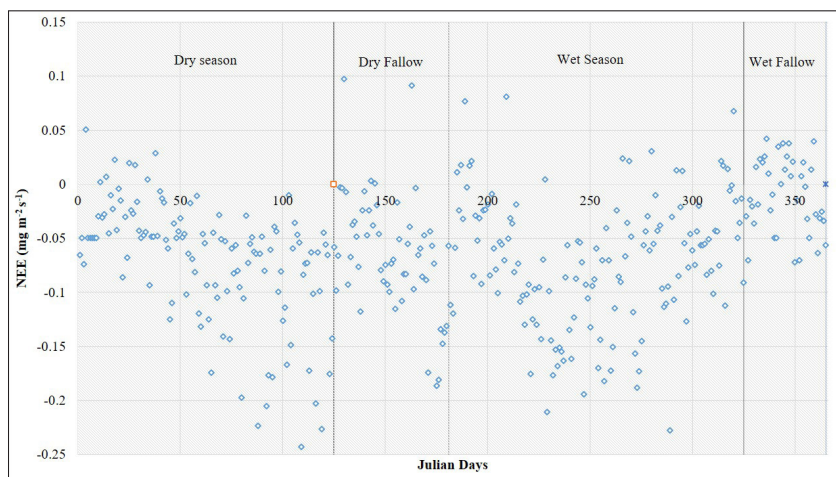


Figure 7: Seasonal variation of daily mean NEE

8.1.1.2 Partitioning NEE into GPP and RE

The NEE is the resultant of CO_2 sinked into photosynthate and the heterotrophic, autotrophic respirations. This can be partitioned into two components *viz.* gross primary productivity (GPP) and ecosystem respiration (RE) (Jung *et al.* 2011). In agroecosystem, the partitioning of carbon fixed in photosynthesis and the carbon spend through respiration have a significant influence on biomass accumulation *i.e.* the rate of plant growth. Moreover, it is important for budgeting carbon at the ecosystem level. Rice ecosystem acts as a source of CO_2 during night as contribution is made from only respiration in absence of photosynthesis; while it acts as a sink of CO_2 during day as CO_2 is assimilated through photosynthesis and released through respiration by rice ecosystem.

Various mathematical models are used for partitioning of NEE into GPP and RE, of which two models (rectangular hyperbola and Q10) are evaluated for lowland rice ecosystem of Cuttack (Chatterjee *et al.* 2020b). The GPP is the CO_2 uptake by the photosynthesis of vegetation and RE is the CO_2 release through respiration of soil, roots, stems and leaves of plants (autotrophic, RE_a and heterotrophic, RE_h).

$$NEE = GPP - RE \text{ -----(Eq 10)}$$

$$NEE = GPP - \text{RE}_a - \text{RE}_h \text{ -----(Eq 11)}$$

The main principle of portioning relies on measuring night time RE (RE_n). It is determined from nighttime NEE. Since there is no GPP at night ($\text{GPP}=0$) as at nighttime NEE (NEE_n) is equal to night time ecosystem respiration (RE_n).

$$NEE_n = RE_n \text{ -----(Eq 12)}$$

Rectangular hyperbola broadly assesses the effects photosynthetically active radiation (PAR) on NEE (Ruimy *et al.* 1995) by using the formula:

$$NEE_{\text{night+day}} = - \left[\frac{\alpha \cdot \beta \cdot Q}{\alpha \cdot Q + \beta} \right] + \gamma \text{ -----(Eq 13)}$$

Where α is apparent ecosystem considerable yield; β is light saturation determined CO_2 uptake rate, NEE; γ is the estimated ecosystem respiration, RE and Q is photosynthetically active radiation, PAR. β is determined as the maximum GPP value which denotes the closeness to the linear response coefficient, and α is determined by the initial slope of the function or ecosystem quantum yield.

On the other hand, the *Q10 method* uses measured nighttime fluxes to predict RE as a function of air temperature. NEE at night is exponentially related to air temperature (T_a) and this relationship is then applied to calculate RE at daytime (RE_d) (Falge *et al.* 2001).

$$RE_n = R_0 Q_{10}^{\frac{(T-T_0)}{10}} \text{ -----(Eq 14)}$$

Where R_0 and Q_{10} are constants; T is the air temperature and T_0 is the reference temperature. Q_{10} describes the temperature sensitivity parameter, here delineating the amount of change in RE for a 10°C change in temperature. The daytime temperature is assumed to respond in a similar way as that of the nighttime RE ($RE_d = RE_n$), the above equation is used for daytime data to calculate daytime RE (RE_d), and NEE is then calculated by $NEE = GPP - RE_d$.

In Cuttack, the ‘Q10’ method reliably yielded better portioning over the ‘rectangular hyperbola’ method in low land rice (Chatterjee *et al.* 2020b). A typical graph partitioning daily average NEE into GPP and RE is shown (Figure 8), in which the GPP and RE varied from -8.11 to -18.92 and 7.83 to $15.45 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively.

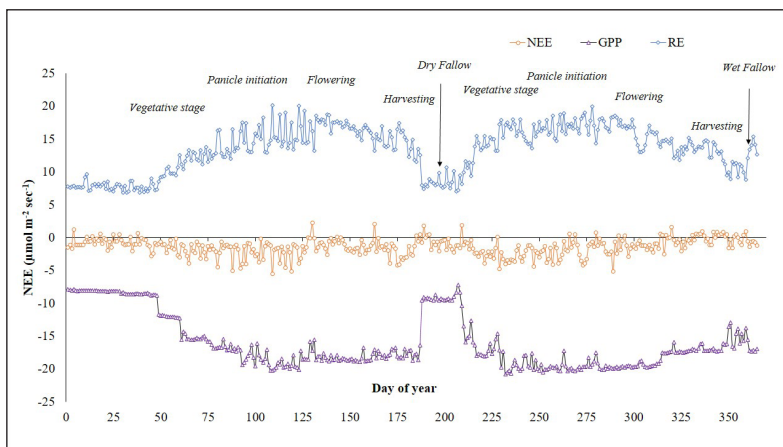


Figure 8: Partitioning of daily average NEE into GPP and RE

8.1.2 Net ecosystem methane exchange

Methane is recognized as one of the most important greenhouse gas in the lowland rice-based ecosystem. For production of methane, three conditions are required, such as the supply of organic sources of carbon, anaerobic environment (Eh: -200 mv or less), and presence of methanogens. The process is influenced by soil labile C content, redox potential, moisture content, pH, and temperature (Guo and Zhou 2007). The release of methane from soil is carried out by ebullition, diffusion from soil to air through water layer and transport through aerenchyma tissue. In agricultural ecosystem, mean vertical flux density of CH₄ is often expressed as net ecosystem methane exchange (NEME), which can be defined as the net exchange of methane between an ecosystem and the atmosphere. The importance of measurement of NEME is important because global warming potential (GWP) of CH₄ is 28–36 over 100 years; therefore, increased methane exchange from lowland rice ecology exert more negative impact to environment as compared to the carbon dioxide exchange. NEME can also guide in the management of lowland rice *viz.* water management and application of C rich material (FYM/compost) to soil.

The NEME measured in lowland rice paddies is influenced by air temperature, soil temperature sensible heat flux and latent heat flux. Basically, methanogenic activities are increased with temperature. More specifically, acetoclastic methanogenesis is intensified with increase of soil temperature which resulted in higher production and emission of methane and increased NEME. The NEME is also influenced by PAR as photosynthesis influence methane transport and release of carbonaceous root exudates which facilitated methane production.

Seasonal variation of NEME is observed due to variability in water depth, soil aeration, methanogens activities and availability of carbonaceous exudates and organic matter throughout the season. The mean of NEME during dry season is lower than the mean NEME during the wet season. During the growth stages, the highest NEME is observed during the active tillering to panicle emission stage of the crop due to higher methanogenic activity and higher soil labile C (acts as substrate) at this stage (Meijide *et al.* 2011; Swain *et al.* 2016, 2018b). It is also observed that the cumulative NEME in dry fallow is lower than the wet fallow (Swain *et al.* 2016).

Diurnal variation of NEME is caused by diurnal changes in temperature and light availability. The highest NEME is found in the afternoon hour (13:30 -14:30 h). During midnight to early morning hour NEME is lower and it starts increasing 10:00 h, reached its peak in the afternoon, which is decreasing further after sunset (Swain *et al.* 2018b).

Inter-annual variation in NEME is controlled by temperature anomalies as it does for NEE. Besides, variation in soil temperature, standing water and radiation are also resulted in inter annual variation of NEME.

An example of diurnal variation of NEME is shown in Cuttack (Swain *et al.* 2018b). Average daily NEME varied from 0.12 to 8.85 mg CH₄ m⁻² h⁻¹ (Figure 9). Mean NEME was lower during dry fallow compared to wet fallow. Average NEME is increased (4.19 mg CH₄ m⁻² h⁻¹) during wet season compared to dry season (2.86 mg CH₄ m⁻² h⁻¹).

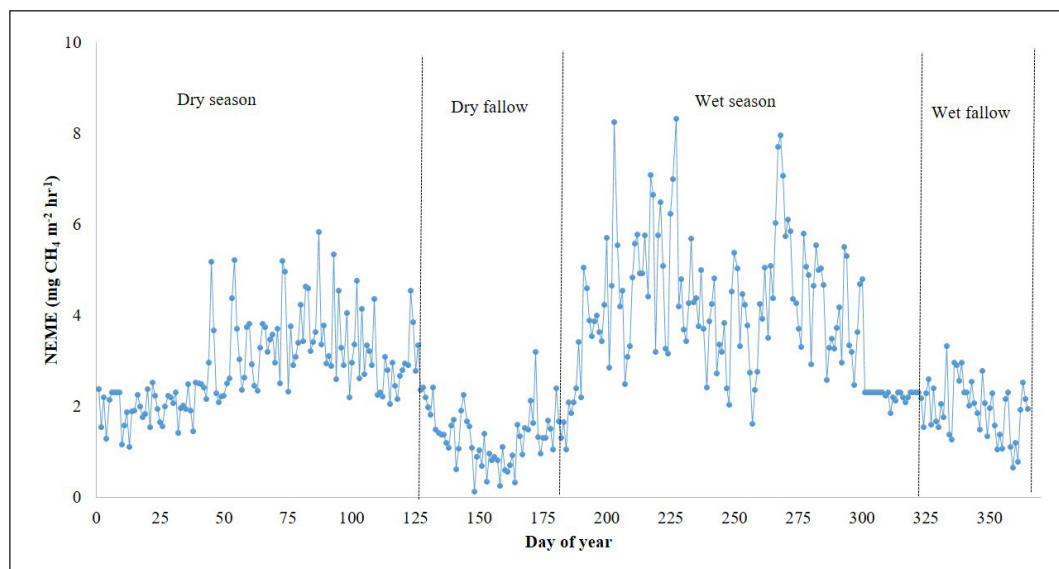


Figure 9: Daily mean NEME during crop growth stages including both the fallow periods

8.1.3 Net ecosystem nitrous oxide exchange

The GWP of N₂O is 298 and lifetime is about 121 years which makes this greenhouse gas more important to be measured at field level (Skiba and Rees 2014). Mostly the orthodox methods of measurement (*e.g.* close manual chamber) are presently replaced by fast-response N₂O analyzers embedded in EC system. Sensor for measurement of net ecosystem nitrous oxide exchange (NENE) is not available at NRRI. However, fast-response N₂O analyzers can be used for real-time measurements of N₂O flux. It is observed that the seasonal variation in N₂O flux is highly dependent on soil moisture rather than soil temperature.

Advantages of EC based measurement of NENE are, (i) these are real-time measurement, (ii) higher reliability and accuracy in the measurement (Huang *et al.* 2014). The main issue in NENE measurement is that the sensor is highly expensive compared to the sensors for CO₂, however, continuous cooling using liquid nitrogen is not required in the new models of the N₂O sensor.

8.1.4 Measuring carbon balance

The carbon balance of the system can be calculated from by the difference between the input and output of carbon. For measuring the carbon balance, the following formula is

used (Smith *et al.* 2010, Bhattacharyya *et al.* 2013; Bhattacharyya *et al.* 2014).

$$NECB = NEP - DOC - FI - HA - VOC - METH - ER + F + I \text{ -----(Eq 15)}$$

where NEP is net ecosystem production which is equivalent to NEE (negative sign), DOC is the loss of C via dissolved organic carbon, FI is C-loss by fire (not practiced, hence ignored), HA is C loss by harvest, VOC is the C loss by volatile organic compound (negligible, Smith *et al.* 2010), METH is the loss of C through CH₄, ER is the C loss by erosion and eluviation and I is the addition of C from farmyard manure and other sources (stubbles, rhizodeposition, aquatic biomass *etc.*). The values of rhizodeposition and aquatic biomass, DOC may be analyzed or adopted from available literature (Bhattacharyya *et al.* 2014).

Various farming operations are involved in the addition of C inputs in terms of addition of organic manures, aquatic biomass, rhizodeposition, CO₂-C assimilation, decomposition of leftover roots and stubbles and C output through harvesting of crop and emission of gaseous C (CH₄ and CO₂). The estimation of C balance provides an insight of C cycling within the ecosystem (Bhattacharyya *et al.* 2014).

The estimated net ecosystem productivity (NEP) from rice-rice ecosystem in Cuttack was +3.83 and +2.51 Mg C ha⁻¹ in dry and wet seasons, while 0.98 and 0.14 Mg C ha⁻¹ in two fallows, respectively (Swain *et al.* 2016). Therefore, the lowland rice ecology behaved as net C sink. However, in support of this study no significant change in total carbon in upper 15 cm was observed, which indicates that this carbon might have lost in lower soil profile or converted to non-measurable pools of labile C (Smith *et al.* 2010).

8.1.5 Water vapour flux

The water vapour is one of the most abundant greenhouse gas, however, the impact of water vapour flux in greenhouse effect is probably less studied. Measurement of water vapour flux is very important for water management, irrigation, agricultural, hydrological modelling and remote sensing. Besides, the measurement of water vapour flux is critical for density correction of fluxes of other atmospheric gasses (CO₂ and CH₄).

The water vapour flux measured during dry season is increased with the increasing growth stages with the progress of crop phenology, the highest value is found in maturity and the lowest in the vegetative stage. The variations in net radiation, maximum temperature and minimum temperature influences water vapour flux (Schneider *et al.* 2010). The diurnal variation for water vapour flux showed a bell-shaped curve reach its peak at 13:30-14:00 IST. In water scarce ecosystem grown with arable crops, the leaf stomata is closed for some time around 14:00 to prevent the moisture loss (Huang *et al.* 2002). However, in water excess situation like rice field, the peak is directly related to net radiation (Chatterjee *et al.* 2019a). After the peak, the water vapour flux decreased slowly and reached its minimum at midnight or early morning before sunrise.

Water vapour flux is controlled by several micrometeorological parameters such as latent heat of vapourization, net radiation, photosynthetically active radiation, air temperature, soil temperature, water temperature, shortwave radiation, evaporation and relative humidity.

In an experiment at NRRI, Cuttack, the relationship between carbon dioxide flux (FCO_2) and water vapour flux (FH_2O) ignoring direction (sign) showed that FCO_2 increased with an increase in FH_2O , and positive correlations ($r^2 = 0.76$ to 0.44) between FCO_2 and FH_2O were observed when data were grouped by growing stage (Figure 10). The positive correlation between FCO_2 and FH_2O is related to the diffusion of water vapour from the leaf stomata to the air and diffusion of CO_2 from the air to stomata (Chatterjee *et al.* 2019a).

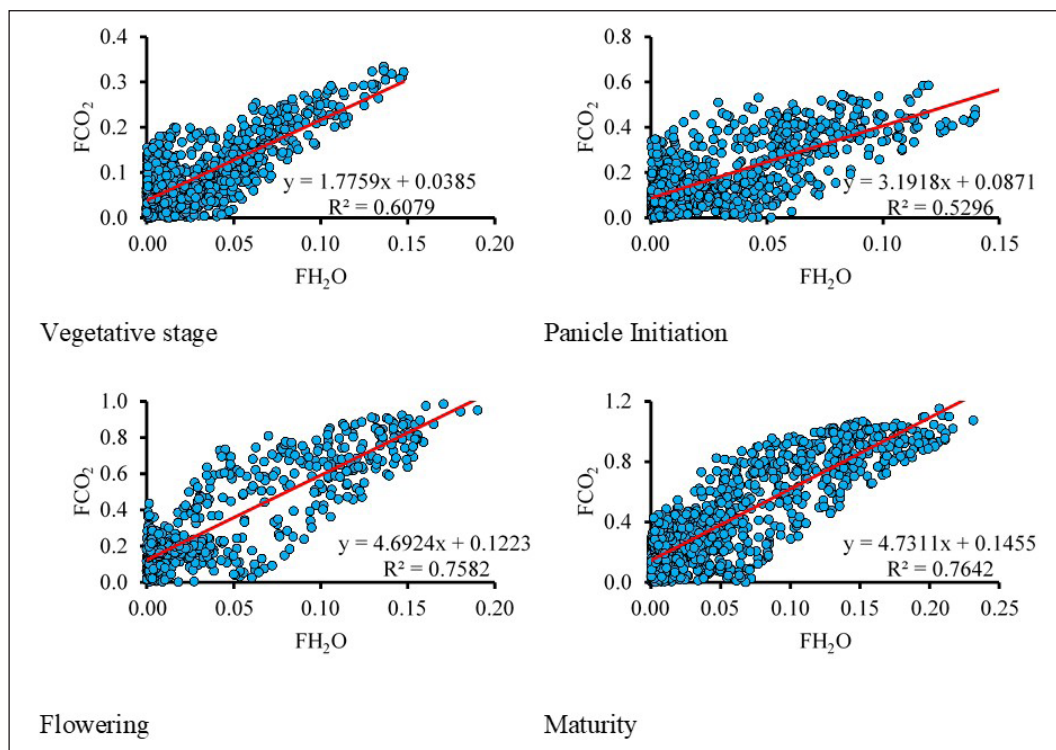


Figure 10: Correlation between FCO_2 and FH_2O in paddy field using half-hourly average data

8.1.6 Actual evapotranspiration

Evapotranspiration (ET) is obtained by cumulating water evaporation and transpiration from a surface area to the atmosphere. Evaporation accounts for water movement to the air from soil, canopy, and water bodies. Actual evapotranspiration (ETa) is the amount of water removed from a surface due to the processes of evaporation and transpiration. It differs from potential evapotranspiration (ETp) which is the water removed through evaporation and transpiration when there is no control of water and the value of ETp is always higher

than ETa. For calculating the ETa is derived from eddy covariance data of latent heat flux (LE) and the air temperature (Ta) (Ding *et al.* 2010).

$$ETa \text{ (mm d}^{-1}\text{)} = \frac{3600 \times LE}{\lambda \times \rho_w} \dots\dots\dots \text{(Eq 16)}$$

where, λ is the latent heat of vaporization (MJ kg⁻¹) which is equal to 2.501–0.00236Ta, ρ_w is the density of water (10³ kg m³) and 3600 is a conversion coefficient of an hour to second.

At NRRI, actual evapotranspiration (ETa) in rice-rice ecosystem was measured by eddy covariance and pan evaporimeter were found in good agreement. ETa increased with the progress of both cropping seasons and found minimum during the fallow periods. The average ETa rate for dry and wet season rice paddy was 2.31 and 2.24 mm d⁻¹, respectively.

8.2 Energy exchange measurement

Energy flux in a given direction is defined as its amount per unit time passing through a unit area normal to that direction (W m⁻¹ or J m⁻² Sec⁻¹). Surface energy exchange is mainly determined by four types of energy fluxes, *i.e.* Rn, H, LE, and G coming into or going out from the surface.

The rice ecosystem has a continuous water layer of 5-8 cm on soil surface that makes it behave different in energy exchange with atmosphere. The productivity of rice depends on various climatic variables like precipitation, temperature, solar radiation, humidity, and PAR. In addition, the heat fluxes are also influenced by the nature and type of vegetation cover. Therefore, energy exchange measurement in rice is a crucial requirement to comprehend and model rice ecosystem and its interaction with the climatic variables including surface energy exchange parameters (Bormann 2011; Chatterjee *et al.* 2019b). In the following subsections, we will discuss energy fluxes measured directly using eddy covariance and those derived from measured fluxes.

8.2.1 Land surface energy flux (sensible, latent and soil heat fluxes)

Sensible heat flux (H) refers to the energy-related to changes in temperature of a gas or object with no change in phase. Latent heat flux (LE) is the energy required to change the state (from solid to liquid and liquid to gas, *vice versa*) of material of a unit mass.

Soil heat flux (G) is the conduction of energy per unit area in response to a temperature gradient. The ground heat flux plates are installed at different soil depths (5, 15 and 30 cm) in which continuously measure the ground heat flux (G) calculated from thermal conductivity of soil (κ), temperature gradient ($\frac{\partial T}{\partial z}$) of particular soil depth (z) and the temperature (T) of that depth.

$$G = \kappa \cdot \frac{\partial T}{\partial z} \dots\dots\dots \text{(Eq 17)}$$

All the three land surface energy flux varies with the progress of rice cultivation. In rice crop, H is more crucial during early growth stage while, LE dominates during active tillering to grain filling and decreases at harvesting. The highest LE, H is observed at flowering stage. H is negative at flowering and grain filling stages. The soil heat flux (G) is highest at grain filling period whereas lowest at harvesting.

Diurnal variations of H, LE and G varies in a unimodal shape. H reach its maxima at 11:00 AM-12:30 PM. The peak value of LE and G reach at 12:30 PM-1:30 PM and 9:00 AM-10:00 AM respectively. As compared with H and G, diurnal variation amplitude of LE is much higher. The H is consistently near zero or negative before sunrise and after sunset, primarily because of absence of insolation and very little turbulence during those hours. Positive upward H during daytime was primarily due to insolation and increased turbulence (Montazar *et al.* 2016). The daily dynamics of G shows a few hours delay in the early morning and starts to change after the sunrise. This could be due to change in height of the rice crop (1.2 m), which induced a delay in soil surface warming (Roxy *et al.* 2014). The diurnal variation in G in different season including the fallows may be caused by many reasons such rainfall events, soil moisture conditions, net radiation, skin temperature, vegetation etc.

In an experiment in NRRI, it was observed that the H accounted for 1-23% of the available energy, while LE was 23-66% of the available energy. LE dominated over H and the magnitude of LE was 1.2-63.9 times higher than H in all the cropping seasons and fallows. Impounding of water in rice field and better canopy cover accounted for higher evapotranspiration which increased LE compared to H. The G comprised of 5-10% of the available energy. During daytime net radiation is the principal contributor of energy flux to the surface, whereas, LE was the main receiver from the surface, while during nighttime, G is the major energy contributors and net radiation, as well as LE, were the main receivers (Swain *et al.* 2018a, 2018c).

8.2.2 Net radiation

Net radiation flux is the balance between incoming and outgoing energy which is influencing the climate. Understanding net radiation is important as the hydrologic cycle is fuelled by it. If incoming radiation exceeds the outgoing radiation then it creates energy surpluses, while the outgoing radiation dominates over incoming radiation then it gives rise to deficits net radiation.

In eddy covariance system, net radiation is measured by 4-component net radiometer which is composed of an upward-facing CM3 pyranometer which measures the incoming solar radiation and a downward-facing CM3 pyranometer which measures the reflected solar radiation. Altogether, four component net radiometer measures incoming shortwave radiation (ISR), incoming longwave radiation (ILR), outgoing shortwave radiation (OSR) and outgoing longwave radiation (OLR). The resultant of these four radiations are used to calculate net radiation (NR).

$$NR = (ISR + ILR) - (OSR + OLR) \text{ -----(Eq 18)}$$

Among different rice growth stages, net radiation (NR) is higher in dry season and fallow compared to wet season and wet fallow, respectively. The peak of NR is observed at 11:30 AM -1:00 PM.

8.2.3 Bowen ratio

Bowen ratio(B) is obtained by the ratio of H and LE. Bowen ratio will give an idea of relative dominance of sensible and latent heat fluxes.

$$B = \frac{H}{LE} \text{ -----(Eq 19)}$$

Higher Bowen ratio indicates that a large portion of Rn is partitioned into LE (Alberto *et al.* 2009). Determination of Bowen ratio is crucial in hydrological cycle, boundary layer properties and weather variability of a region and can be used as an indicator of water stress (Alves and Pereira 2000). Average B in rice is ranged from 0.21-0.64. Large variation in B is observed during the fallow periods as compared to the cropping seasons. For rice across the world, B is lower than other arable crops which is because of the lower stomatal resistance and greater photosynthetic capacity of rice (Wilson *et al.* 2002).

8.2.4 Albedo

The albedo (α) is shortwave reflectivity measured as a ratio of incoming and reflected solar radiation and it varies between 0 and 1.

$$\alpha = \frac{OSR}{ISR} \text{ -----(Eq 20)}$$

It is expressed as a number or sometimes as percentage and is measured on a scale from 0-1. The zero represents no reflection of a perfect black body, while 1 represents perfect reflection of white surface. In rice field, albedo varies from 0.09 to 0.24. During the cropping season, albedo increases after rice transplanting upto panicle initiation stage, then it diminishes started from flowering stage to the maturity stage. The average albedo of the fallow period is slightly higher than their respective cropping seasons. The diurnal mean of albedo is positive and found in the range from morning 6:00 IST to evening 18:00 IST.

8.2.5 Soil, air and skin temperature

Soil temperature affects many physical, chemical, and biological soil properties, and growth of plants and microorganisms growing in it. Soil temperature also controls soil water content, its movement and retention. In eddy covariance system it is measured by soil temperature probe inserted at various depths. The air temperature is controlled by incoming radiation from the sun. More specifically, it describes the kinetic energy of the constituent gases of air. As gas molecules move more quickly, air temperature increases. It is measured by fine wire thermocouple and air temperature-relative humidity (ATRH) sensors in eddy covariance system. Skin temperature is the overall temperature of the earth surface covered

with water layer and vegetation. It is not measured directly from eddy covariance system, rather it can be derived from outgoing long wave radiation (OLR) or may be downloaded from online sources (Wielicki *et al.* 1996).

In a rice-rice ecosystem at Cuttack, it was observed that soil, air and skin temperatures were highest in dry fallow. Air temperature increased with increasing net radiation from 7:00 IST onwards upto evening 19:00 IST. The difference between mean skin temperature and mean air temperature was more (6.1 K) in dry fallow. During dry season, the skin temperature remain unaffected during the initial stages of crop growth and increased later (Tsai *et al.* 2007).

8.2.6 Aerodynamic, canopy and climatological resistances

Aerodynamic (r_a), canopy (r_c) and climatological (r_i) resistances are also termed as drag forces. Aerodynamic resistance is the component of force exerted by the air on the heat that is parallel and opposite to the direction of heat flow. Similarly, canopy resistance refers to the drag force offered by crop canopy on the water vapour which is in opposite direction to the water vapour flow. Aerodynamic resistance for heat transfer and canopy resistance for evapotranspiration are determined by equations 21 and 22.

$$r_a = \frac{\rho_a C_p (T_s - T_a)}{H} \text{ ----- (Eq 21)}$$

$$r_c = \frac{\rho_a L_v (q_s - q_a)}{LE} - r_a \text{ ----- (Eq 22)}$$

where, ρ_a , c_p and L_v are the density of air, specific heat capacity of the air, latent heat of vaporization, respectively; q_s is the saturated specific humidity, q_a is specific humidity of air, T_a is air temperature, and T_s is the skin temperature,

Climatological resistance is measured as the ratio of vapour pressure deficit to surface available energy (V).

$$r_i = \frac{\rho_a L_v (q_s - q_a)}{V} \text{ ----- (Eq 23)}$$

Aerodynamic, canopy and climatological resistances are increased with the progress of cropping season and found minimum during the fallow periods.

8.2.7 Energy balance and its closure

Energy budgeting and energy balance closure (EBC) in flooded rice are different from other upland crops since a continuous water layer is present on the soil surface (Alberto *et al.* 2011; Tsai *et al.* 2007). The surface energy budget in rice can be expressed as the sum of surface LE and H flux equivalent to all other energy sinks and sources (Tsai *et al.* 2007). This is based on conservation of energy.

$$= LE + H \text{ ----- (Eq 24)}$$

where V is available heat flux at the surface; NR is the net radiation; G is the soil heat flux; S is the heat storage in a layer of soil having a boundary in between soil surface and the plane of insertion of soil heat flux sensors; W is the heat storage in the standing water; C is the heat storage in canopy; F is the photosynthetic energy flux.

The EBC is examined using three procedures: *ordinary least squares*, *energy balance ratio* and *residual heat flux*. As perfect closure can ever be achieved, these methods used to indicates the underestimation or overestimation of the available heat flux. These three methods of EBC can also be compared to see how good the curve is fitted with the data points.

a. *Ordinary least squares*

In the first method, the *ordinary least squares* (OLS) relationship is measured between the relationship of turbulence heat flux ($H + LE$) against available heat flux (V) and linear regression coefficients (slope and intercept) are derived (Wohlfahrt and Widmoser 2013). This method is considered as effective assuming there are no random errors in the independent variable. This can be expressed as:

$$LE + H = a(R_n - G) + b \text{ ----- (Eq 25)}$$

where a and b are the slope and intercept of linear regression, respectively. The perfect closure is achieved when the intercept is zero and the slope is 1. ‘a’ is basically an intercept. When the energy balance closure is perfectly closed then $a=0$ and a perfect curve passing at 45° ($b=1$) with both X axis ($R_n - G$) and Y axis ($H + LE$) are achieved. However, it is practically impossible. The EBC can be improved if storage terms are included. In reality, there are two situations arise *i.e.* overestimation and underestimation depending on the seasonal variations.

- When, $b < 1$ and $a > 0$ then $R_n - G = 0$, $H + LE$ have positive value *i.e.* overestimation
- When, $b > 1$ and $a < 0$ then When $R_n - G = 0$, $H + LE$ have negative value *i.e.* underestimation

In an experiment carried out at Cuttack using OLS to measure EBC, it was observed that the coefficient of determination (R^2) ranged 0.66-0.85 for dry season; 0.63-0.83 for dry fallow; 0.38-0.49 for wet season and 0.67-0.80 for wet fallow (Figure 11). The value of R^2 is more than 60% in all the seasons except wet season. The slope was higher in dry season (0.77-0.89) as compared to wet season (0.38-0.47) (Figure 11).

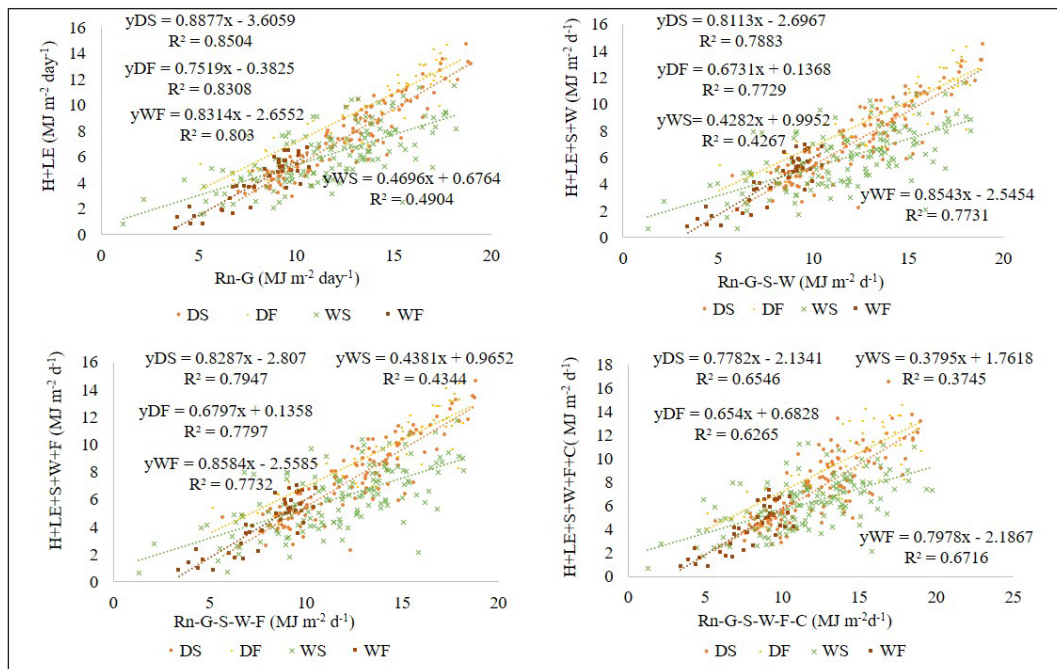


Figure 11: Energy balance closure measurement by ordinary least square
 (a) Rn-G vs. H+LE, (b) Rn-G-S-W vs. H+LE+S+W, (c) Rn-G-S-W-F vs. H+LE+S+W+F,
 (d) Rn-G-S-W-F-C vs. H+LE+S+W+F+C

b. Energy balance ratio

Energy balance ratio (EBR) is also used to evaluate the closure (Wilson *et al.* 2002). This is expressed as the ratio of cumulative turbulence heat fluxes (LE + H) and available heat flux (V) over a time period.

$$EBR = \frac{\sum(LE + H)}{\sum(V)} \text{ ----- (Eq 26)}$$

With the standard EBR values (Equation 24) correction of different storage terms (S, W, F and C) help to get more precise EBR values.

The EBC measured by EBR in Cuttack showed that the coefficients did not varied among the cropping seasons and fallows (Table 3). However, the value of EBR was low in wet season compared to dry season and fallows. Highest mean value of EBR (EBR I) among the four seasons was observed as 0.72 in dry fallow. This implies only 72% of the available energy was balanced during this period. This value falls further in other periods. The dry season and dry fallow were almost free from rainfall, except a few overcast days in these seasons. Hence, the energy components were almost balanced during the rain-free days. When applying the correction to H and LE by adding the storage term, a new and improved EBC could be obtained. These new closures (EBR II-IV) slightly improves the energy balance in wet season and wet fallow.

Table 3: Summary of energy balance closure using energy balance ratio (EBR)

Sea- sons	I			II			III			IV		
	LE+H	V	EBR I	LE+H +S+W	V -S- W	EBR II	LE+H +S+W +F	V -S- W -F	EBR III	LE+H +S+W +F+C	V -S-W -F -C	EBR IV
DS	922.9	1535.5	0.60	920.5	1537.9	0.60	927.7	1530.7	0.61	931.1	1527.3	0.61
DF	560.0	779.7	0.72	543.8	795.8	0.68	546.8	792.9	0.69	557.5	782.2	0.71
WS	883.0	1658.1	0.53	866.3	1674.7	0.52	874.9	1666.2	0.53	884.7	1656.3	0.53
WF	167.0	331.2	0.50	173.5	324.6	0.53	173.9	324.2	0.54	171.5	326.6	0.53

All the parameters shown in the table are the average value of the half-hourly fluxes ($\text{MJ m}^{-2} \text{ day}^{-1}$) except EBR I-IV, which are ratio. LE+H, turbulent heat flux; V, available heat flux; S, soil heat storage; W, water heat storage; F, photosynthetic energy flux; C, canopy heat storage; EBR, energy balance ratio; DS, dry season; DF, dry fallow; WS, wet season; and WF, wet fallow.

c. Residual heat flux

The third method *i.e.* residual heat flux (RHF) quantifies the inconsistency between the available heat flux (V) and turbulence heat flux (H+LE) and provide information about whether the LE+H measured by the EC system is overestimated or underestimated. This method evaluates the degree of EBC achieved (Wohlfahrt and Widmoser 2013; Cava *et al.* 2008).

$$RHF = V - H - LE \text{ ----- (Eq 27)}$$

The RHF should be zero when the surface energy budget is closed. If RHF is greater than zero, then the supply of energy is larger than the loss of energy; else, the result is the reverse.

A comparison between the all the season in Cuttack showed average residual heat flux (RHF) was increasing positively from dry season to wet fallow and its value is 10.3-12.0% higher in wet season as compared to dry season and 8.3% higher in dry fallow than wet fallow. It should be equal to zero when the surface energy budget is perfectly closed. Since the average value of RHF is more than zero in all the seasons across years, the available heat flux was greater than the cumulative turbulent flux (Liu *et al.* 2017). This imbalance is much more in wet season and wet fallow.

For measuring energy balance closure, storage terms (heat storage in a layer of soil having a boundary in between soil surface and the plane of insertion of soil heat flux sensor, heat storage in the standing water, heat storage in canopy and photosynthetic energy flux) are included to get better closure. When three methods are compared in lowland paddy, it is

found that the EBC estimated using RHF is the most suitable way to calculate closure as it can distinguish different seasons (dry season, dry fallow, wet season, wet fallow) distinctively, followed by OLS.

Effective closing the surface energy balance provides a high level of confidence in the flux observation method. Imperfect closure tells us measuring errors of the eddy covariance system or not inclusion of heat storage measurement. However, recent studies depict imperfect energy balance closure is a scale problem (Masseroni *et al.* 2014). Assessing energy balance closure can be used to assess the data quality (Aubinet *et al.* 2000). The errors in measurement of CO₂ fluxes is sometimes related to incomplete energy balance closure (Liu *et al.* 2006; Anthoni *et al.* 2002).

Changes in water depth during wet season contributes to difficulties in closing the energy budget. The rainfall brings freshwater into the system which resulted in advection of energy into the system. Moreover maintaining the standard depth of water in wet season is also difficult after the rainfall event. More uncertainty was involved in the measurement of energy balance closure in wet season.

8.2.8 Estimation of water balance

Estimation of water balance is required to assess the present status and trends in availability of water resource and it helps in strengthening the water management decision. The water balance equation describes the flow of water in its various forms, into and out of a hydrological system (Falalakis and Gemitzi 2020):

$$P + L = ET + SR + I \text{ ----- (Eq 28)}$$

Where P is precipitation, ET is evapotranspiration, SR is the surface runoff, I is the infiltration to the vadose zone and to groundwater and L is moisture loss from soil in the form of capillary rise or transport through vegetation. ET can be modelled through eddy covariance data and rest of the parameters can be measured at field level to check the water balance.

9. Advantages and drawbacks of flux measured through eddy covariance system

Advantages

- The eddy covariance data is a continuous in-situ measurements over the large area without disturbing the area over which fluxes are measured.
- The flux data are highly reliable, defensible and verifiable.
- The data obtained are measured with fast sampling and high precision.
- The measurement system are automated and provides continuous data.

Drawbacks

- There are some limitations using eddy covariance approach. The flux tower provides point information specific to a single ecosystem type. Besides, there are chances of having random measurement errors. The source of such errors are due to power fluctuations, insects and dirt contamination in the sensors and errors associated with turbulent transport (Hollinger and Richardson 2005).
- The technique is mathematically complex and requires significant care in setting up and processing data.
- Eddy towers can provide information specific to a single ecosystem type or condition. If mixed ecosystem is present then it is very difficult to predict which component of the system contributes to the flux.
- Many a time noisy flux is obtained and this uncertainty is mainly because of random measurement error.
- It requires a number of assumption and correction and demands careful design, execution and processing.
- The study area needed to be flat, homogeneous and must represent the similar ecology for measurement, which is sometimes not possible in natural system.

10. Conclusion

Measurement of greenhouse gas flux and energy flux using eddy covariance provide a point measurement over a large area (fetch 2-3 ha). Most of these mass and energy exchange flux values are used for micro-meteorological models. Various parameters measured using the eddy covariance system can potentially be used as a source of default values for various models, especially in Eastern India.

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