Trends in Climatic Features and Greenhouse Gas Exchange of Crops in Scarcity Zone (Baramati) of Western Maharashtra

ICAR-National Institute of Abiotic Stress Management
(Indian Council of Agricultural Research)
Malegaon, Baramati - 413 115, Pune

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Preface

Indian agriculture is inherently vulnerable to various weather vagaries. Due to aberrations in monsoon behaviour in terms of onset, distribution and withdrawal, farmers continue to face hardships in agricultural operations and often experience huge crop losses. Vulnerability is increasing with climate change, incidences of extreme weather events as droughts, floods, heat or cold waves, cyclones and hailstorms. Though with advances in science, weather forecasts and agro-advisories at district level have improved considerably, deviations of weather forecast at micro-scale i.e. village or block level are more common especially in water scarce regions where inherent rainfall is already low and its spatio-temporal variability is high.

Detail agro-climatic characterization at micro levels form the very basis of climate resilient agriculture as it helps in selecting right kind of crops, adjustment of cultivation and efficient water management based on rainfall, thermal and radiation regimes, overall risk assessment, input provisioning and watershed management. The above information should be integrated in a bottom-up approach to develop a national climate information bank. This in turn will help in improving the skill of weather forecasts, agro-advisories and contingency planning at block or village level. This will also be useful in validating the regional climate models, re-classification of agro-climatic zones under the changing climate scenario, better implementation of weather based crop insurance schemes and other decision making tools that rely on weather parameters.

I sincerely hope that the information contained in this document will be useful for climate researchers, local agro-advisory units, farmers and other stakeholders. Keeping in view the existing climatic differences across regions as well as the dearth of information on crop ecosystem-atmosphere gas exchange, there is a genuine need to carry out similar studies in various agro-climatic zones of the country.

February, 2015

(P S Minhas)

Acknowledgement

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Contents

Summary

Knowledge of agro-climatic features at micro level helps in adoption of climate smart management practices by the farming community. It enables the decision makers at local level in scientific crop planning, better risk preparedness, formulating appropriate contingency plans and reaping higher amount of agri-produce through minimisation of the impacts of climatic variability. Climate of a place, in broader terms, not only includes the averages or normals of the weather variables but also information on other aspects such as frequency and intensity of extreme weather events and quantum of exchanges of energy and trace gases between vegetation and the atmosphere.

Agro-climatic characteristics and rainfall pattern widely varies within Pune district of the western Maharashtra region. Though the Baramati *taluka* falls under the scarcity agro-climatic zone (AZ 95/MH-6), high water demanding sugarcane farming forms the backbone of its economy. Hence, any change in its climatic conditions is likely to show socio-economic impacts. So far, the broader agro-climatic aspects of Baramati area have not been characterized in the context of climate change. Therefore, with the objectives of providing options for climate smart agriculture, the long-term weather data recorded at Malegaon was analysed to characterise its features and trends along with some of the recent field experimentations at NIASM. The typical features are as follows:

- Average weekly total rainfall exceeds 5 mm in 24 no. of weeks. Except one week that falls during mid-November, rest of those weeks fall between mid-May and October.
- No trend was obvious in annual rainfall but for increase in the days with rainfall >2.5 mm, particularly those with 2.5-10 mm and 10-25 mm rainfall during August.
- Frequency of occurrence of meteorological drought is once in 4 years while the agricultural drought occurs almost in alternate years.
- The ratio between reference crop evapo-transpiration (ETref) and Class A open pan evaporation (Pan-E) varied between 0.70 (in June) and 1.00 (in February).
- Overall climatic PAR efficiency i.e. PAR: Global Radiation ratio on annual basis was 0.35. Diurnally, the above ratio varied between 0.19 and 0.66 depending primarily on the solar angle and cloudiness. Climatic efficiency during the *kharif* and *rabi* growing seasons were 0.36 and 0.33, respectively.
- Crop ecosystems-atmosphere exchanges of the most important greenhouse gas i.e. CO_2 were quantified for *Dhaincha*, soybean and wheat which acted as sinks with net uptake rates of 1.5, 2.0 and 1.0 $\mu mol\ m^{-2}\ s^{-1}$, respectively.

1. Introduction

The ever-growing population pressure and the threat of climate change are posing challenges to the food security of the country. The potential crop yields can be realised on sustainable basis, only if the resource management practices, among other factors, are in harmony with the prevailing agro-climatic conditions. For achieving the former, the management practices must be devised for optimal utilisation of favourable and minimization of the risks of adverse weather conditions. Climate, in simple terms, is the synthesis of weather conditions of a given location. It refers to the characteristic condition of the atmosphere deduced from repeated observations over a sufficiently long period. The weather refers to the short term such as day to day or within the day fluctuations of the atmosphere those occur with continuous exchanges of energy and mass within and/or between the earth surface and the atmosphere. Such exchanges are results of the processes for uniformity in net surface radiation energy. Acting over an extended period of time, these processes accumulate to become climate. Rather being a statistical average, climate is an aggregate of environmental conditions involving heat, moisture and gaseous motion. Thus attempt to characterize climate of a sector must include information on extremes in addition to means, trends, fluctuations and probabilities of occurrence of various weather events.

So far, region specific potential of the climate as a natural resource for agricultural production processes has not been utilized in the country. Nevertheless with an aim to offer appropriate technologies for crop production and natural resources management and prioritizing areas for scientific and operational interventions, the country had been divided into various agro-climatic and agro-ecological zones. Weather based agro-advisory services are undertaken through AMFUs (Agromet Field Units) which at present receive weather forecasts and issue agricultural management advisories with district as the base unit. However, the weather does not follow administrative boundaries and there is considerable heterogeneity in terms of weather, specifically rainfall. To effectively implement weather based agro-advisory services for smaller, more homogeneous units such as village or block (also called as *tehsil*, *taluka* or *mandal*) skill of forecasts needs considerable improvements. Thus to upgrade both the quality of forecast and the agro-advisories, quality weather data repository must be built up from a network of observatories, those adequately representing each zone, and characterization of climate at a micro level.

Agro-climatic characterization at a micro scale would help in local adjustment of crop cultivation practices, irrigation schedules based on expectancy of rainfall, micro-watershed management, reclassifying agro-climate zones under the changing climate scenario, better implementation of weather based crop insurance schemes and other decisions that rely on weather variables. Alongwith measurements of routine weather variables, it is now increasingly being felt to develop an information bank on biosphere-atmosphere exchange of greenhouse gases with respect to various soil or cropping systems in various agro-climatic regions. Such information acquired through a network within and across the countries would help in more reliable prediction of climate change at regional and global levels and feedback of changing climate on agriculture. Outcome of such research initiatives would also help in formulating appropriate adaptation and/or mitigation strategies for agriculture in the climate change regime.

Micro-scale characterization of climatic conditions assumes still greater significance for arid, semi-arid and plateau regions interspersed with hills where rainfall shows high spatial variability. Therefore, variable soil moisture regime associated with quantity and distribution of rainfall becomes the most limiting factor for crop production. Even where manoeuvring of moisture regimes is possible, thermal and radiation regimes also influence the choice of crops, cropping patterns and the optimum dates of sowing for targeting higher crop yields. In addition, any weather abnormalities such as cyclones, floods, droughts, hailstorms, frost, high winds and extreme temperatures impact agricultural productivity and cause associated adverse effects on socio-economic conditions. Keeping above in view, an attempt has been made to characterize the agro-climatic aspects of Baramati area in the context of climate change and these should help in adopting different options of climate smart agriculture.

2. Study Area : General Features

National Institute of Abiotic Stress Management (NIASM), Malegaon Khurd is situated at 18°09′ N latitude and 74°30′ E longitude in Baramati *taluka*, which is located in the eastern part of Pune district and is a part of the desh or western Maharashtra region of India (Fig.1). As per the agro-climatic zonation, the area falls under the scarcity zone (NARP zone: AZ-95) and physio-graphically, is a part of *deccan* plateau with average elevation of about 550 m AMSL. It is also under the *madhya* Maharashtra sub-division that is one of the 36 meteorological sub-divisions of the country that India Meteorological Department (IMD) has classified for rainfall forecasts during the monsoon season.

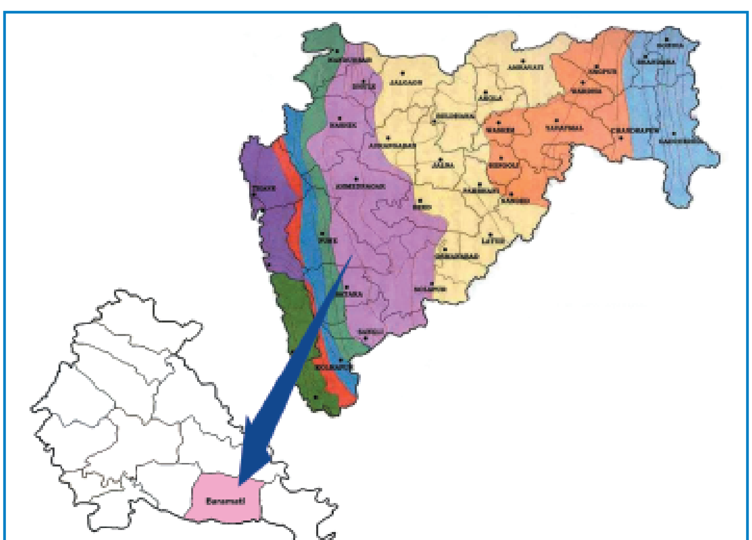


Fig. 1. Agro-climatic zones of Maharashtra showing location of Baramati *tehsil*

The area is characterized by low effective rainfall, which is erratic in nature and is highly drought-prone. It has good air transparency, strong solar radiation, and sparse cover of natural vegetation. Loamy black soils of the area are shallow to medium in depth, with deep black soils as inclusion and shallow well drained soils with fairly good clay percentage and slight stoniness. Only one third of area of the *taluka* is irrigated and the rest is rainfed. General physical and agro-climatic features, soil and crop information are presented in table 1 and table 2, respectively.

3. Climate at Baramati

Long-term weather data recorded daily at Maharashtra State Irrigation Department Office, Malegaon Colony, Baramati, situated about three kilometres from the NIASM campus was analysed to have an insight of the local climate. Daily data records are available for three variables, viz. the maximum and minimum temperature and rainfall corresponding to the period 1986-2011. For other weather variables daily data are available for a part of the aforesaid period. Statistics with respect to these variables are described in sections 3.1 to 3.4.

Table 1. General physical and agro-climatic features of Baramati *taluka* area

Feature	Description
Physiography	Deccan Plateau Major areas of the *taluka* are having very gentle slope between 1-3 % and moderate slope between 8-15 %
General Climate	Hot semi-arid
Meteorological Sub-division	*Madhya* (central) Maharashtra
Resource Development Region (Planning Commission)	Western Plateau and Hills region
Agro-climatic Region (NARP-ICAR)	Scarcity Zone (AZ-95)
State Agro-climatic Region (Maharashtra)	Western Maharashtra Scarcity Zone (MH-6)
Agro-eco sub-region (NBSS & LUP)	South Western Maharashtra & North Karnataka Plateau (6.1 K4Dd3)
Annual Temperature	Mean Daily ~ 25 °C
Annual Rainfall	Long term average is ~ 600 mm that occurs in about 35 rainy days; bimodal pattern of rainfall with two peaks of in June/ July and in September
Normal onset of Monsoon	Second week of June
Normal withdrawal of Monsoon	Fourth week of September
Potential Evapotranspiration	1500-1800 mm
Length of Growing Period (LGP)	60-140 days
Climatic Constraints	Delayed onset of monsoon, early cessation and long dry spells sometimes spanning upto10 weeks. Meteorological drought occurs once in three to four years
Other similar Region	Eastern half of Pune, Satara and Sangli, Solapur, Osmanabad, Bid and Ahmadnagar districts of Maharashtra. Bijapur (northern part), Raichur and Dharwad (eastern part) of Karnataka.

Source: Adapted and updated from http://www.mahaagri.gov.in/CropWeather/AgroClimaticZone.html; http://www.imdagrimet.gov.in; http://agricoop.nic.in/Farm%20Mech.%20PDF/05024-01.pdf; http://dacnet.nic.in/farmer/new/dac/District.asp

3.1 Temperature

3.1.1 Daily

Long term average annual daily mean, maximum and minimum temperatures for this location are 26.4, 33.1 and 19.7 °C, respectively. During the years, 1986-2011 annual daily means varied between 24.7 and 27.5 °C. Recorded extremes of daily mean temperature during the aforesaid period were 14 and 37 °C whereas that of maximum temperature were 45 °C (on 28 May, 2003 and 20 March, 2004) and 16 °C (on 21 December, 1987). For daily minimum temperature extremes were 5 °C (26 & 27 January, 2006) and 33 °C (9 May, 1988). The daily diurnal differences ranged between 28 °C and 1 °C and its annual mean stood at 13.4 °C.

Table 2. Soil types and major crops

Feature	Description
Soil	**General types:** Slightly deep, well drained, fine, calcareous soils on gently to very gently sloping lands with mesas and buttes with moderate erosion and slight or no stoniness Shallow, well drained, clayey soils on gently sloping land with moderate erosion Deep, moderately well drained, strongly calcareous, fine soils on gently sloping plains and valleys with moderate erosion are found in narrow stretches along the river banks. **Major soil orders:** Vertisols, Inceptisols and Entisols **Major soil groups:** Ustorthents, Ustropepts, Chromusterts **Available Water holding Capacity:** Low to medium (about 100 mm/m for light soils such as Inceptisols) **Infiltration rate:** 6-7 mm/h **Fertility status:** poor in nitrogen, low to medium in phosphate & well supplied in potash
Crops and cropping pattern	Because of bimodal distribution of rainfall two cropping systems are practiced. During *kharif*, shallow and poor moisture retentive soils are cultivated. Medium deep soils that have fairly good moisture holding capacity are diverted to *rabi* cropping. For the entire MH-6 zone, *Kharif* cropping comprises about 25-30%. Major crops of Baramati *taluka* area during *khaif* season are bajra, maize, soybean and tur and during *rabi* season jowar, wheat, chickpea and maize. Crop productivity in rainfed areas is rather low in both the seasons. In areas irrigated by Nira canal (about one third area of the *taluka* is irrigated), most areas are under sugarcane crop and have good productivity.

Source: Adapted and updated from Slope Map, MRSAC-Nagpur; District Social & Economical Review Report, Economics & Statistical Department, Pune District (2002); Commissionerate of Agriculture, Pune district, Maharashtra State

3.1.2 Weekly

Long-term averages for mean temperature of various weeks in a year vary between 31.8 (±1.8) and 21.4 (±2.0) °C and these correspond to week 19 (7-13 May) and 51 (17-23 December), respectively. Warmest and coldest weeks, based on mean temperature that prevailed during the weeks were week 18 in 1993 (35.6 °C) and 51 in 1987 (15.3 °C), respectively. The maximum annual variation in weekly mean temperature has been found to occur with respect to week 6 (5-11 February) and the minimum variation in week 31 (30 July-5 August). The corresponding ranges were 14.6 °C (16.9 °C in 1987 and 31.4 °C in 2001) and 3.5 °C (27.9 °C in 1987 and 24.4 °C in 2011), respectively.

Weekly means of the maximum temperature varied between 39.7 (±2.6) and 29.3 (±2.2) °C corresponding to the week 18 (30 April-6 May) and week 1 (1-7 January), respectively. On the other hand, weekly means of minimum temperature varied between 24.0 (±2.6) and 13.2 (±2.2) °C, those correspond to the week 19 (7-13 May) and week 51 (17-23 December), respectively. Average diurnal difference varied between 17.9 °C (week 10) and 7.7 °C (week 29 & 30) and extremes occurred in week 15 (1999) and week 42 (1987) that recorded values of 25.9 °C and 3.0 °C, respectively. Long-term means of the daily and weekly maximum, minimum and mean temperatures and extremes are given in table 3 while the normal weekly temperatures are plotted in figure 2.

3.1.3 Monthly

The monthly mean temperature varies between 22.0 °C (December) and 31.4 °C (May). Maximum temperature reaches its peak in May (39.1 °C) and dips to 29.9 °C in December. For minimum temperature, May records the highest (23.7 °C) and December as well as January the lowest value.

Table 3. Long term averages for daily and weekly maximum, minimum and mean temperatures

Daily			
Statistics	Mean Temp. (°C)	Max. Temp. (°C)	Min. Temp. (°C)
Mean	26.4	33.1	19.7
Extremes	37.0, 14.0	45.0, 16.0	33.0, 5.0

Weekly						
Statistics	Mean Temp. (°C)		Max. Temp. (°C)		Min. Temp. (°C)	
	Max	Min	Max	Min	Max	Min
Mean	31.8 (W19)	21.4 (W51)	39.7 (W18)	29.3 (W1)	24.0 (W19)	13.2 (W51)
Extremes	35.6 (W18, 1993)	15.3 (W51, 1987)	43.3 (W12, 2004)	17.4 (W51, 1987)	29.6 (W19, 1988)	7.6 (W4, 2006)

N.B. 'W' denotes the number for the standard meteorological week

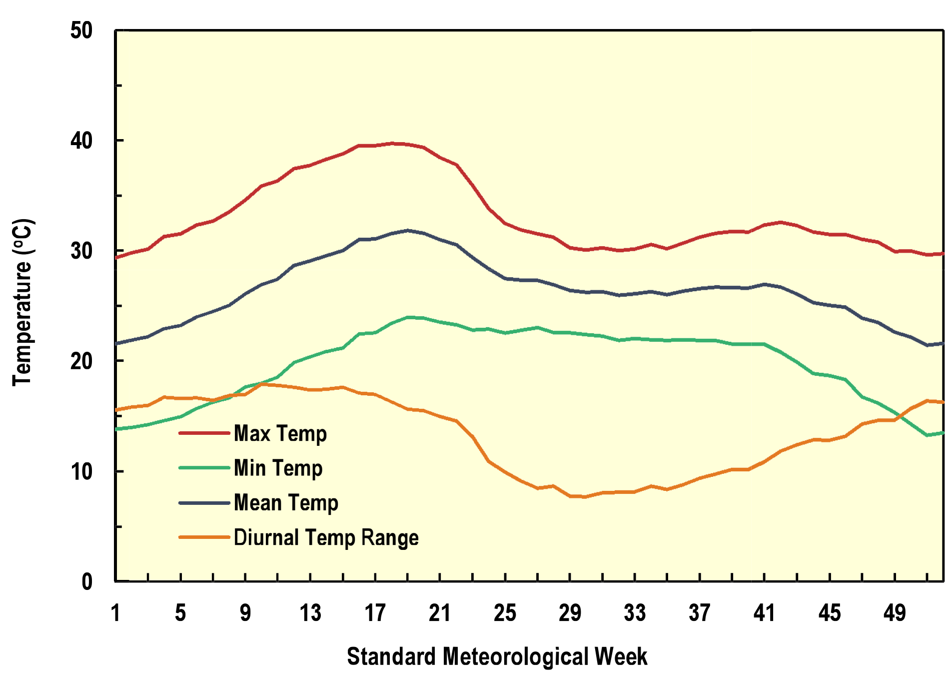


Fig. 2. Weekly minimum, maximum and mean temperatures and average diurnal ranges during 1986-2011

3.1.4 Extreme Temperature Frequency

During the period 1986-2011, on an average, the number of days in a year in which the maximum temperature exceeded 40 °C was 22, however, there was a large variation year to year. In 1987, no day recorded the maximum temperature higher than 40 °C whereas in 2010 as many as 47 days exceeded the same. For a higher temperature threshold of 42 °C, on an average only 2 days (frequency ranging between 0 and 8 days) in a year could be found that exceeds such limit. The maximum temperature crossing 43 °C is a rare phenomenon at this location with only 10 such days can be found during the aforesaid period.

Day's minimum temperature dipping below 14 °C, particularly during winter months were more common than not at this location with an average 39 no. of days per year witnessed such condition. For temperature < 13 °C, < 12 °C, < 11 °C and < 10 °C, annual average frequencies stood at 28, 18, 12 and 5 days, respectively. Occurrences of daily minimum temperature in the range of 7-10 °C have become more frequent since 2001. In 2006, five days and in 2008, one day had minimum temperature between 5 and 6 °C, respectively. The annual frequencies of number of days in which the maximum and minimum temperatures cross aforesaid thresholds are provided in Appendix-I.

3.2 Humidity

Relative humidity measured at the standard hours in the morning (RH I) and afternoon (RH II) during the period 1995 and 2000 were used for computation of monthly statistics. RH I varied between 56 per cent (April) and 81 per cent (July and September). On the other hand, variation in RH II was between 36 (April) and 62 per cent (July). Annual mean for the daily average RH stood at 60 per cent (Fig.3). Higher diurnal ranges in RH were observed in the months of February, March and June when it was more than 20 %. Lowest diurnal range was observed in the month of July (10 %). Other months that showed a diurnal range (< 15 %) were November, December and January.

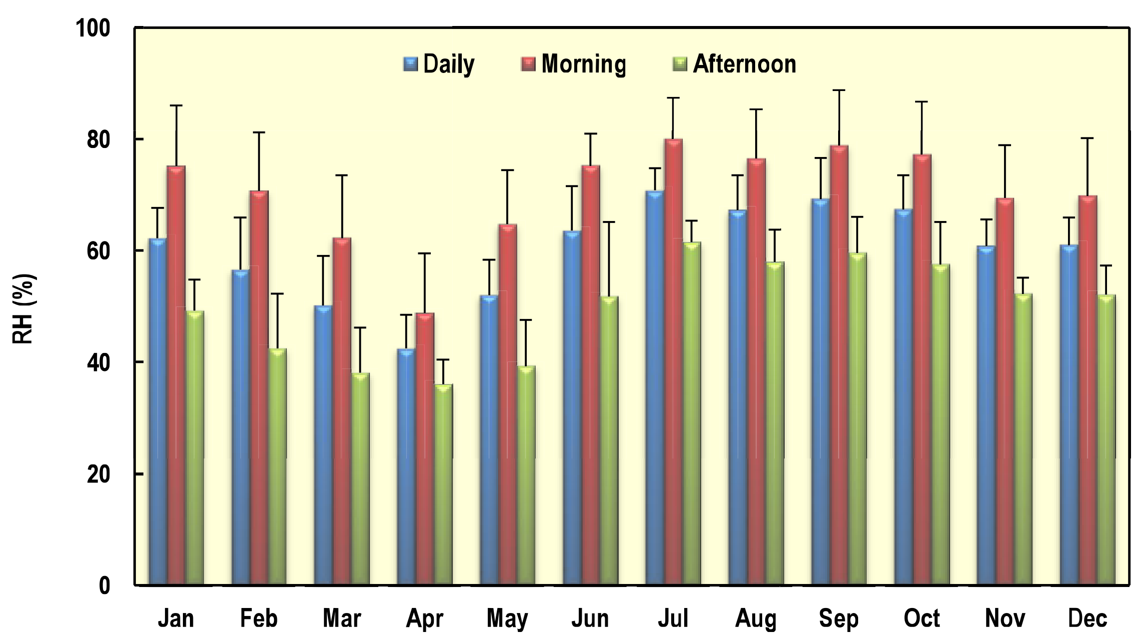


Fig. 3. Relative humidity (RH) in various months (1995-2000)

3.3 Rainfall

Annual rainfall averaged 588 mm for the period 1986-2011 of which about 71 and 22 per cent occurs during southwest monsoon (June-September) and post-monsoon (October-December) period, respectively. The maximum rainfall is received normally during September (159.4 mm) followed by June (113.1 mm) (Fig. 4). In the post-monsoon season, highest rainfall normally occurs in October (104 mm) followed by November (14.7 mm) and during the summer season in May (39.6 mm). Normal rainfall for July and August is 66.3 and 72.9 mm, respectively. Other months of the year, viz. December, January, February, March and April together receive rainfall < 20 mm. The variability in rainfall during south-west and the post-monsoon season is 39 and 88 per cent, respectively while the CV is 37 per cent for the annual rainfall. Effective rainfall is received only during the period May-October.

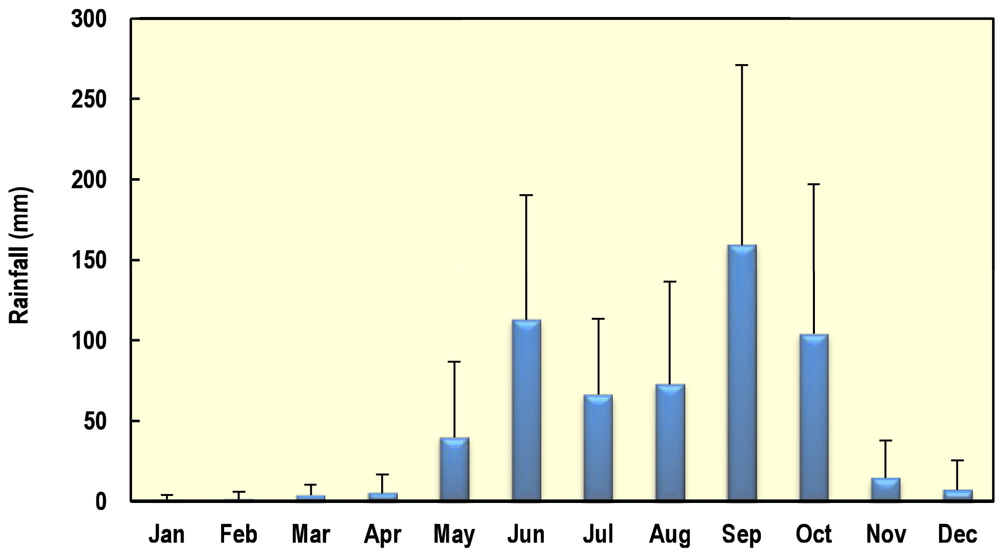


Fig. 4. Monthly rainfall and its standard deviations (1986-2011)

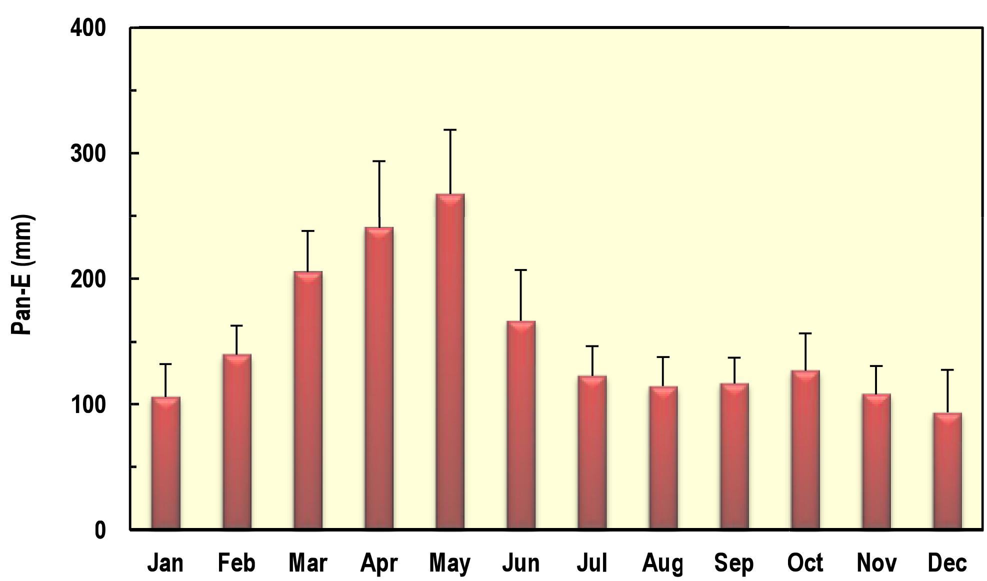


Fig. 5. Monthly pan evaporation and its standard deviations (1995-2011)

3.4 Open pan evaporation (Pan-E)

Annual class A open pan evaporation (Pan-E) averaged 1810 mm which is about 3 times the rainfall. The highest evaporative demand occurs during May (8.6 mm d^{-1}) whereas the lowest is in December (3.0 mm d^{-1}). The maximum Pan-E (2245 mm) was recorded during 2000 and the minimum in 2004 (1497 mm), respectively (Fig. 5). The annual average of daily Pan-E was 5.0 mm and the recorded highest single day Pan-E was 14.5 mm. Weekly average Pan-E varies between 9.0 mm d^{-1} (week 20) and 2.9 mmd^{-1} (weeks 51 & 52). Monthly climatic features are summarized in table 4.

Table 4. Long-term average values of temperature, relative humidity, rainfall and open pan evaporation

Weather Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Means
Tmax (°C)	30.3	32.8	36.6	39.0	39.1	34.0	30.8	30.2	31.2	32.2	31.3	29.9	33.1
Tmin (°C)	14.2	16.1	19.0	21.8	23.7	22.8	22.6	22.0	21.8	20.8	17.7	14.2	19.7
Tmean (°C)	22.2	24.5	27.8	30.4	31.4	28.4	26.7	26.1	26.5	26.5	24.5	22.0	26.4
RH I (%)*	75	71	62	49	65	75	80	77	79	77	69	70	71
RH II (%)*	49	42	38	36	39	52	62	58	60	58	52	52	50
RH daily (%)*	62	57	50	42	52	64	71	67	69	67	61	61	60
Rainfall (mm)	0.8	1.2	3.7	5.3	39.6	113.1	66.3	72.9	159.4	104.0	14.7	7.0	588***
Pan-E (mm)**	106.1	139.7	205.7	241.0	267.6	166.6	123.0	114.5	116.8	126.9	108.4	93.5	1810***

N.B. *average for the period 1995-2000; ** average for the period 1995-2011; ***annual total;all unmarked corresponds to averaging period, 1986-2011

4. Rainfall Patterns

The average annual or seasonal rainfall is not sufficient to decide the crop production activities. Rather the cropping pattern and crop calendars require the knowledge of rainfall distribution pattern those decide the timings of major soil and crop management practices. Moreover due to high degree of variability compared with other meteorological variables, the dependable rainfall computed at different probability levels can help in several water related decisions especially in rainfed agriculture, dam water management and irrigation structure engineering. Further, the changes in rainfall pattern and occurrences of extreme rain events provide valuable insight for the decision by planners at the local/regional level.

4.1 Weekly Rainfall Distribution

4.1.1. Normals and Dependable Rainfall

Weekly rainfall means were computed along with dependable rainfall at various probability levels using incomplete gamma distribution (Fig. 6; Appendix-II). Long term average (LTA) was >20 mm in case of 12 weeks. Week no. 40 has the highest average rainfall (47.2 mm) whereas weeks 37 to 40, falling during the months of September and October have averages greater than 35 mm. Week 24 has the highest average rainfall (36.4 mm) followed by week 23 (31.4 mm) during the summer monsoon season. Assured rainfall higher than 5 mm at 75 % probability level could be expected in six no. of weeks whereas at 90 % probability level the maximum weekly rainfall that could be expected is 2.3 mm only.

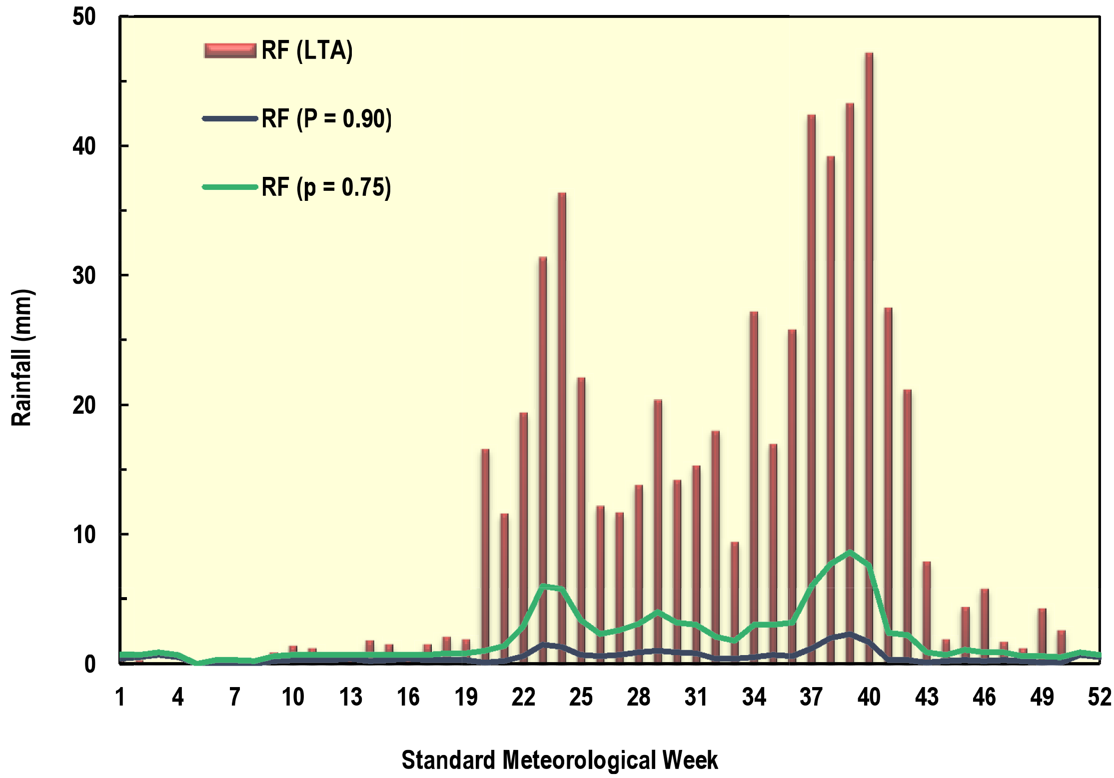


Fig. 6. Weekly average and dependable rainfall (p =0.75 and 0.90)

4.1.2 Weekly Rainfall: Initial and Conditional Probabilities

Since rainfall is highly variable, the initial and conditional probabilities of rainfall are useful for taking decision on agriculture operations and for irrigation management. Rainfall probability for a period (e.g. week) irrespective of the rainfall situation in earlier period (e.g. preceding week or weeks) is termed as initial probability whereas considering those of the previous period is defined as conditional probability. The notation for the probability (P) of a week being a wet (W) when the preceding week is a wet (W) or dry (D) is abbreviated as P(W/W) and P(W/D), respectively.

Only the week 39 has more than 75 % probability of receiving rainfall between 10-20 mm. Week 40 shows a probability higher than 50% for 30-40 mm rainfall. There were one week each in all the four seasons that has 100% conditional probability. These were P(W/W) for 10-20 mm (week 20; pre-monsoon season), 20-30 mm (week 49; winter season), 30-40 mm (week 46; post-monsoon season) and > 50 mm (week 36; monsoon season). Initial and conditional probabilities for receiving different amounts of rainfall in all the weeks of a year are presented in figure 7.

4.2 Rainfall Extremes

Variability in rainfall during (1986-2011) was assessed based on the deviation from the long term average rainfall. The four rainfall groups considered following the criteria of India Meteorological Department (IMD) were excess (> 20 %), normal (19 to -19 %), deficit (-20 to -59 %) and scanty (< -59 %). Number of years under each category, extreme rainfall years and amounts that occurred during the southwest

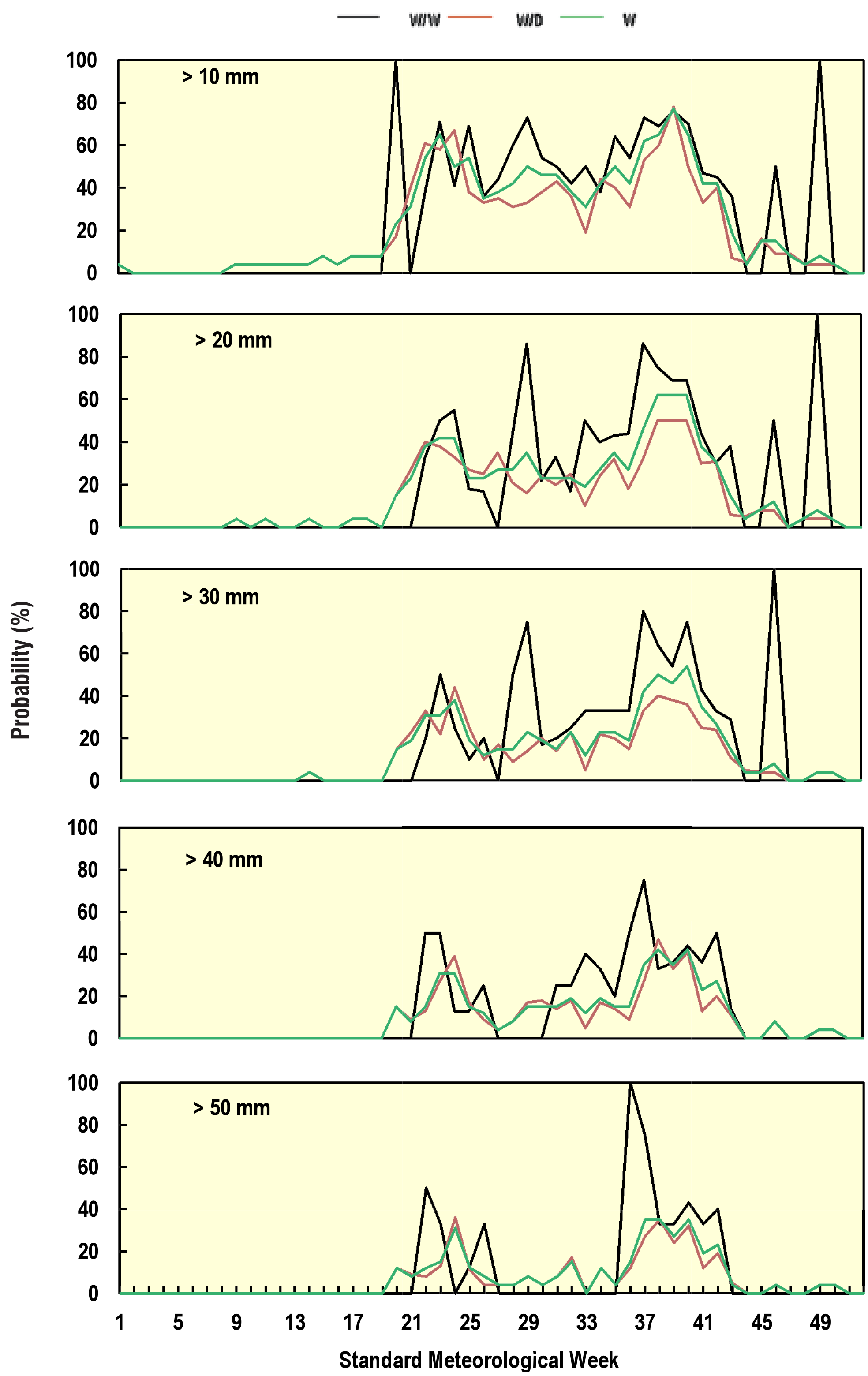


Fig. 7. Initial and conditional probabilities of receiving rainfall in all different weeks of a year

monsoon (June-September) and post monsoon (October-December) seasons are given in table 5. During the aforesaid period, SW and post monsoon rainfall were in the normal range in 10 and 3 number of years, respectively. In case of annual total rainfall, 14 number of years received normal rainfall. Single day highest rainfall (136 mm) was recorded on 23rd June, 2007. Total number of days during which rainfall exceeded 50 mm were 60.

Table 5. Years under various rainfall classes and extremes during 1986-2011

Season	Number of years in rainfall category				Rainfall Total (mm)	
	Excess	Normal	Deficit	Scanty	Highest (year)	Lowest (year)
SW Monsoon (June-September)	7	10	8	1	762 (2010)	151 (2003)
Post-Monsoon (October-December)	9	3	3	11	410 (1993)	0 (2003)
Annual Rainfall	5	14	6	1	1145 (2009)	151 (2003)

4.3 Rainfall Intensity

Average number of rainy days (rainfall >2.5 mm) per month during the period June and October ranged between 5.1 and 7.4 (Fig. 8). However, the occurrences of heavy precipitation day (rainfall > 10 mm) are more during September, June and October than July and August resulting in considerably lower rainfall totals during the later months. Annual time series of no. of rainy days under various intensity classes is presented in figure 9.

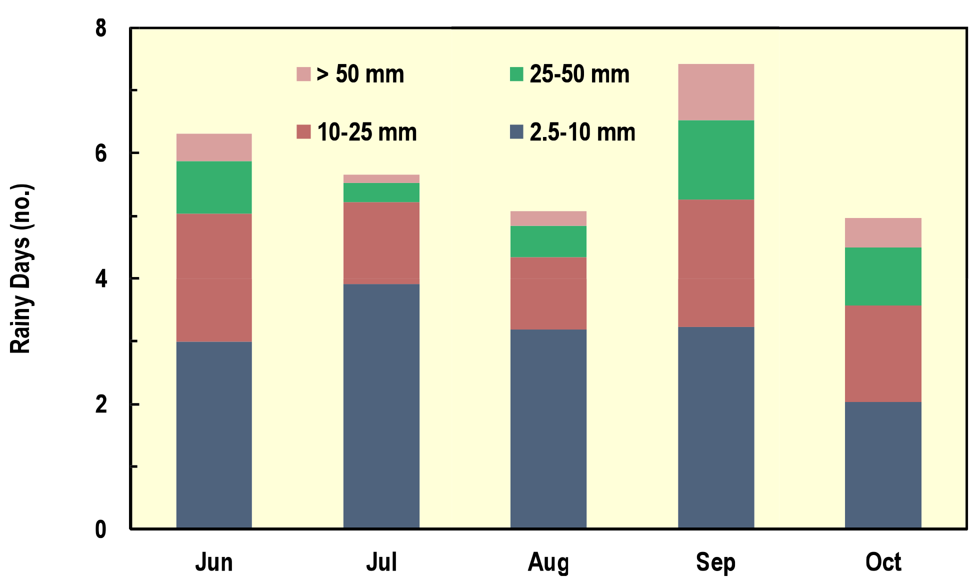


Fig. 8. Rainfall intensity distribution in various rainy months

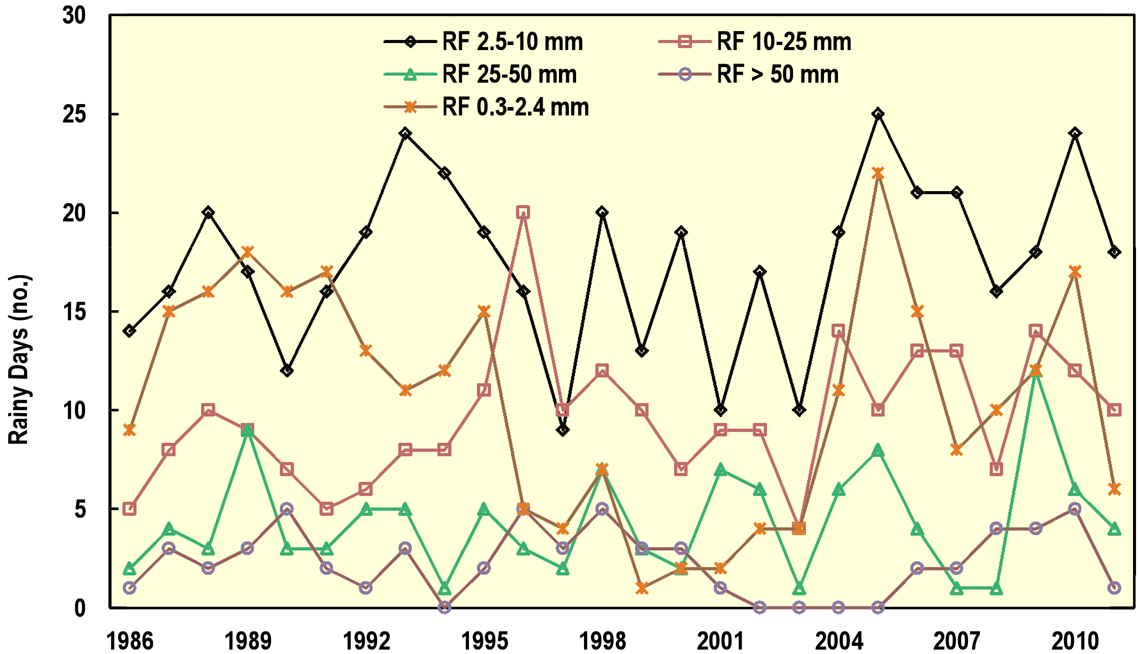
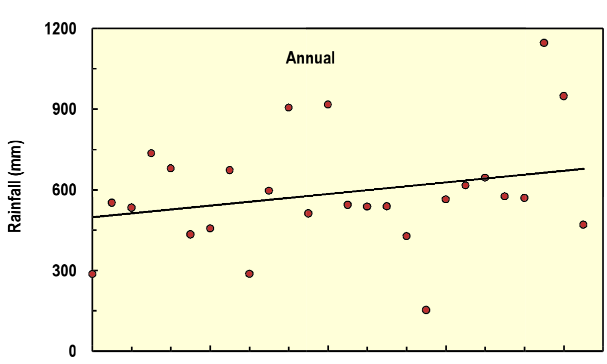


Fig. 9. Annual time series of no. of rainy days under various intensity classes during 1986-2011

Trend analysis revealed that southwest-monsoon rainfall has slightly increasing trend ($R^2 = 0.15$, $P = 0.05$) whereas, post-monsoon and total annual rainfall are not showing any trend (Fig. 10). Indications of increase in the number of days with rainfall >2.5 mm ($R^2 = 0.35$, $P < 0.01$) is apparent for the month of August, particularly in the rainfall intensities 2.5-10 mm ($R^2 = 0.21$, $P < 0.05$) and 10-25 mm ($R^2 = 0.41$, $P < 0.01$). There is no change in rainfall or its distribution pattern in other months and seasons (Fig. 11). Thus on the whole, no appreciable changes are occurring in either monsoon or annual rainfall at Baramati but rainfall now occurs in slightly less number of rainy days with higher frequency of heavy precipitation events.



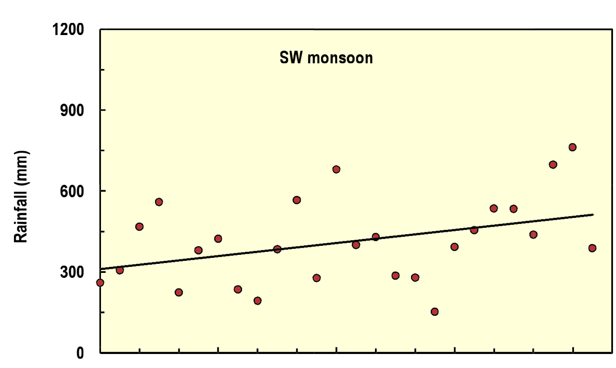


Fig. 10. Time trends of annual and southwest monsoon season rainfall during 1986-2011

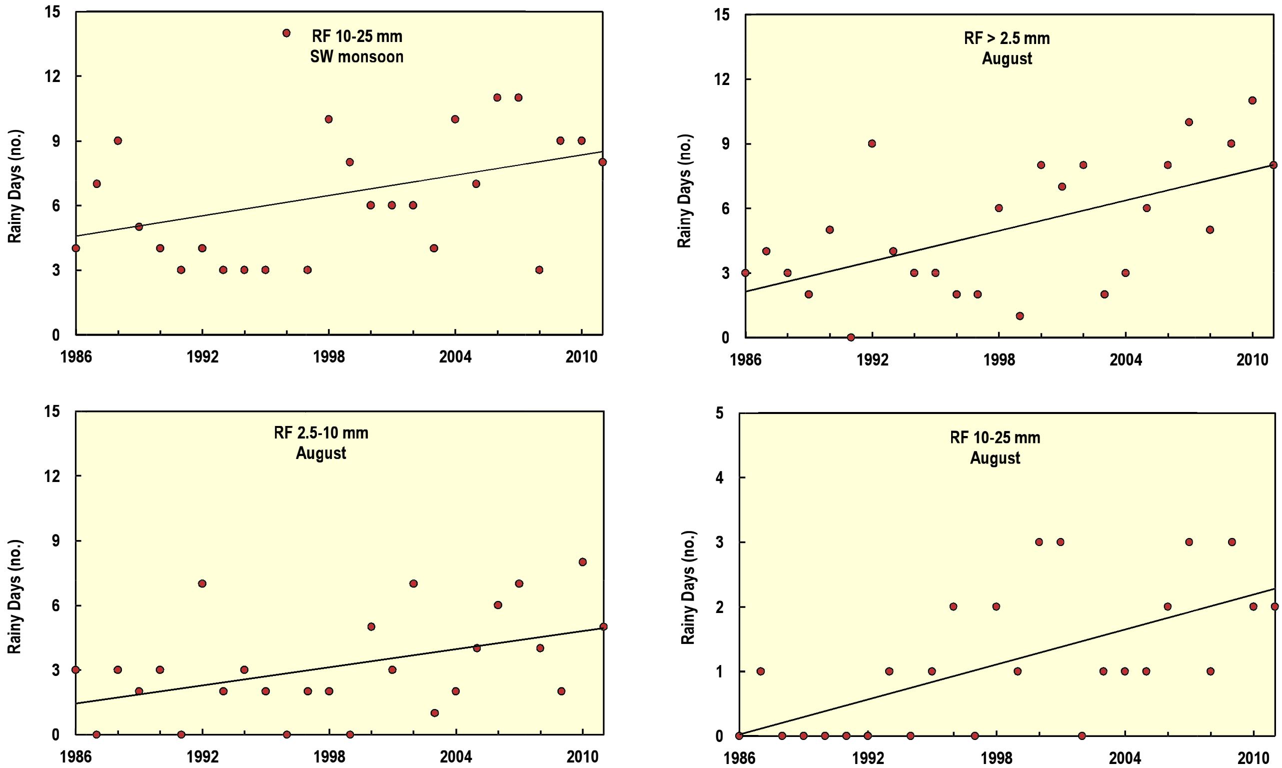


Fig. 11. Time trends of number of rainy days of various intensities in specific season and month during 1986-2011

5. Drought

There are different approaches to define drought. India Meteorological Department (IMD) has defined drought based on meteorological conditions arising out of rainfall deficiency compared to the long-term average or normal during a given period. Generally, a week is considered as the minimum duration for which droughts are to be considered. If the deficiency in rainfall is 26 to 50%, the situation is termed as moderate meteorological drought and if it exceeds 50% then it is severe drought.

For agricultural usage, the distribution rather than the total rainfall is more important, particularly for rainfed areas. IMD has laid out separate criteria for such situation to recognize agricultural drought. When the rainfall for a week is half of the normal or less provided the normal for that week is 5 mm or more and if this continues for 4 consecutive weeks between middle of May to October, when 80 % of the country's crops are sown, it is considered as agricultural drought. However, for micro analysis with respect to Baramati area, the aforesaid period of investigation for agricultural drought analysis was chosen in such a manner that it coincides with its major sowing time windows. In Baramati, *kharif* sowing is done with the onset of monsoon i.e. in the second week of June and the *rabi* sowing normally starts in October. The frequency of occurrence of meteorological and agricultural drought worked out for Baramati shows that during 1986-2011, meteorological drought was witnessed in six no. of years with the annual rainfall shortages were more than 25 %. However, agricultural drought situation prevailed in as many as 16 years. Five years i.e. 1986, 1991, 1994, 2002 and 2003 witnessed both types of droughts. Interestingly, the year 2011 received 415 mm of rainfall that fulfilled the criteria for meteorological drought but not for an agricultural drought. The year 2003 was the worst with rainfall of 151 mm only. The area is classified as chronically drought affected with a strong probability of occurrence of agricultural drought in consecutive years. Annual rainfall for agricultural drought affected years and block of weeks that witnessed severe meteorological drought leading to the agricultural drought are given in table 6.

6. Reference Evapo-transpiration

During the period between October, 2013 to October, 2014, open pan evaporation (Pan-E) varied between 3.5 mm (December) and 7.6 mm (April and May). Reference crop evapotranspiration (ETref) computed using FAO 56 standard Penmann-Monteith equation, ranged between 2.9 mm (December) and 5.7 mm (May) (Fig. 12). Monthly rate of Pan-E showed a consistently increasing trend during January and June and a consistent decreasing trend during October to December. During monsoon, in the months of July, August and September, pan evaporation fluctuated as per the prevailing radiation and cloud and rainfall situation. With the exception of March to June, changes in ETref followed that of Pan-E (Fig. 13). The ratio ETref/Pan-E varied as per the climatic situation of various months. These were found to be 0.72 in October, 0.77 in November, 0.70 in June and 0.77 in May. It becomes relatively low in the months April to July. During the later months the rate of Pan-E remains high due to high climatic water demand but plant canopy is unable to match up the same on account of bulk surface resistance arising out of insufficient soil moisture and/or stomatal closure. On the contrary, during months when potential climatic water demand remains low at this place the ratio value tends more nearer to 1.0. These months were December to February.

Table 6. Agricultural drought years (1986-2011)

Year	Drought Period (No. of consecutive weeks)	Annual Rainfall (mm)
1986	W 25-W 30 (6); W 40-W 43 (4)	287
1987	W 27-W 31 (5); W 34-W 37 (4)	553
1988	W 40-W 43 (4)	532
1989	W 31-W 36 (6)	736
1990	W 34-W 39 (6)	679
1991	W 31-W 37 (7); W 39-W 43 (5)	433
1992	W 40-W 43 (4)	456
1994	W 30-W 34 (5); W 36-W 41 (6)	286
1995	W 30-W 34 (5)	596
1997	W 26-W 30 (5); W 32-W 37 (6)	511
1999	W 30-W 34 (5)	543
2002	W 33-W 40 (8)	427
2003	W 29-W 33 (5); W 35-W 43 (9)	151
2004	W 32-W 36 (5)	564
2007	W 39-W 43 (5)	575
2008	W 25-W 30 (6); W 38-W 41 (4)	570

As there were good number of cloudy days and considerable precipitation occurred in the months of March (80.4 mm), August (191.7 mm) and September (73.7 mm) in the year 2014, the ratio value were found to be slightly higher and in contrast to their preceding and succeeding months

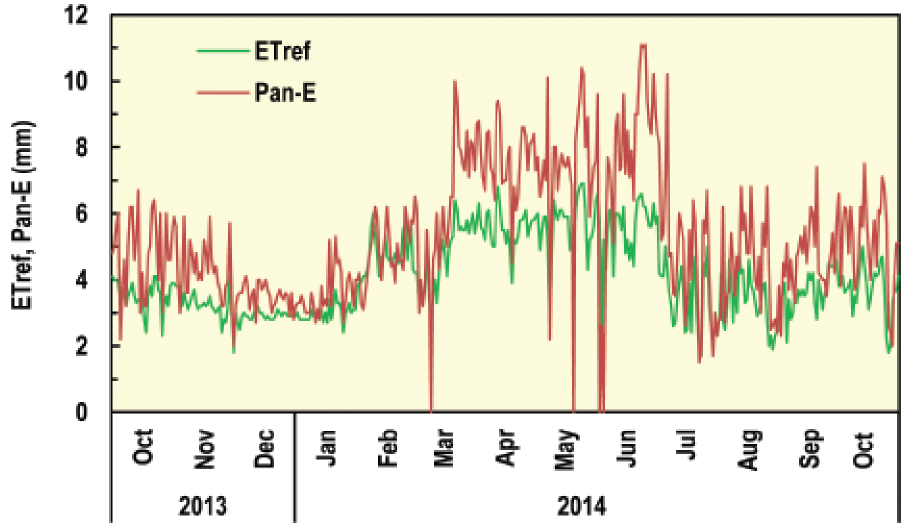


Fig. 12. Time series of daily reference evapotranspiration (ETref) and pan evaporation (Pan-E)

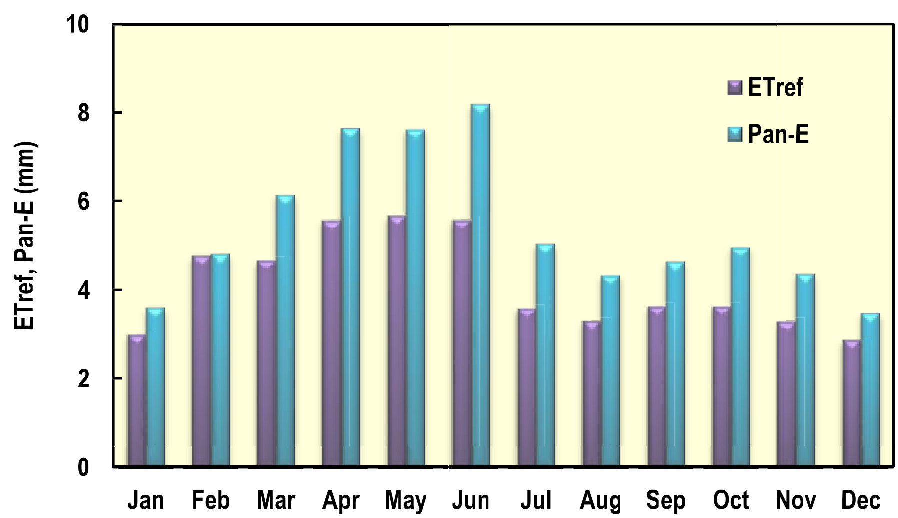


Fig. 13. Monthly dynamics of reference evapotranspiration (ETref) and pan evaporation (Pan-E)

7. Radiation Dynamics

Net radiation and its shortwave and longwave components were monitored for bare soil conditions at NIASM research farm. Data pertaining to the period between September, 2013 and September, 2014 were used to compute various statistics and construct the average diurnal dynamics on annual and monthly time scales (Fig. 14; Appendix-III). Average net shortwave radiation was 364.9 Wm^{-2} during the period between 0700 hr IST and 1930 hr IST and the average maximum intensity was found to occur at 13:00 hr IST. Average loss of net radiation from the soil surface in the longwave range was at 85.9 Wm^{-2} during the entire day-night time cycle. The minimum loss, on an average, was found to occur at 05:30 hr IST and that of the maximum at 13:30 hr IST. The corresponding averages were 52.5 and 151.4 Wm^{-2}, respectively. In case of net radiation during the day-night cycle, it varied between 540.2 Wm^{-2} i.e. net radiation gain by the earth surface (occurred at 13:00 hr IST) and 65.7 Wm^{-2} (occurred at 20:00 hr IST) which was a net loss from the earth surface towards the atmosphere. The diurnal average value for the aforesaid stood at 111.8 Wm^{-2}.

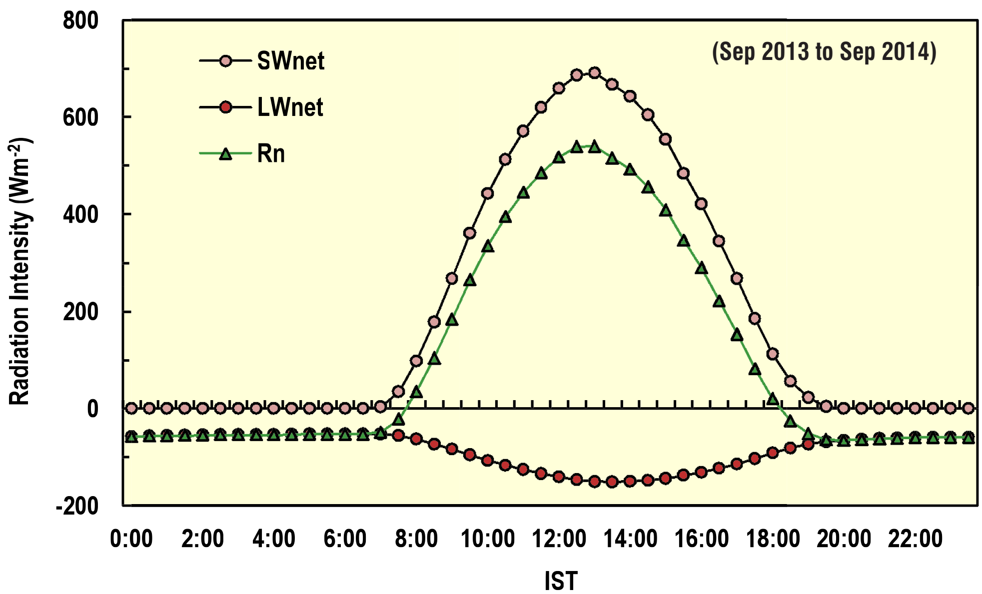


Fig. 14. Average diurnal dynamics of net shortwave (SWnet), net long wave (LWnet) and net radiation (Rn)

Mean daytime (0630 hr IST to 1830 hr IST i.e. 0600 hr LMT to 1800 hr LMT) intensity of net shortwave radiation varied during the year between 310.9 Wm^{-2} (January) and 485.6 Wm^{-2} (May) and the annual mean intensity was 403.4 Wm^{-2} (Table 7). Net long wave radiation remained outward from the earth surface towards the atmosphere throughout the year. However, due to rainfall and higher soil moisture the magnitude of such heat escape was low during the monsoon and lowest value of monthly intensity was recorded during July (62.7 Wm^{-2}). The intensity of net outgoing long wave radiation was higher during the period November-April with highest value recorded in February (142.9 Wm^{-2}). Monthly means of net radiation intensity during daytime hours varied between 208.2 (November) and 364.4 Wm^{-2} (May). During the entire diurnal cycle, the aforesaid statistics for net outgoing long wave radiation ranged between 47 Wm^{-2} (July) and 110.5 Wm^{-2} (February) whereas that of net radiation ranged between 69.6 Wm^{-2} (November) and 152.5 Wm^{-2} (May).

Table 7. Daytime mean values of net shortwave, net longwave and net radiation for different months

Months	Net Shortwave Radiation (Wm^{-2})	Net longwave Radiation (Wm^{-2})	Net Radiation (Wm^{-2})
January	310.9	-124.4	226.6
February	463.7	-142.9	282.1
March	472.2	-136.8	315.7
April	485.4	-137.3	348.2
May	485.6	-121.1	364.4
June	456.6	-119.2	337.4
July	333.0	-62.7	270.3
August	361.8	-65.7	296.1
September	352.0	-74.5	277.6
October	366.6	-102.0	264.6
November	361.0	-137.8	208.2
December	392.5	-132.2	227.6
Annual Mean	403.4	-113.0	284.9

N.B. Negative sign associated with the net long wave radiation indicates the above radiative flux is towards the atmosphere from the earth surface

8. PAR / Insolation Dynamics

Photo-synthetically active radiation (PAR) plays a key role in the growth and development of plants and describing the productivity. The availability of PAR at any location depends on several factors such as latitude, longitude and altitude of the place, time of the day, cloudiness, water vapour, aerosol and dust load of the local atmosphere (Bat-Oyun et al., 2012). Geostationary and polar satellite based insolation data products at various time scales such as half-hourly to monthly periods are now available from various sources and are increasingly being used to simulate vegetation primary productivity and crop yields at regional level (Nayak et al., 2010; Saha et al., 2012). However, information on climatic efficiency i.e. the conversion ratio for deriving PAR from insolation data has not been reported for different agro-climatic zones of India. Keeping above in view, routine measurements of insolation and PAR have been initiated at NIASM agromet observatory which typically represents the semi-arid deccan plateau region of India. Continuous automated measurements of PAR and insolation were undertaken for one year using a line quantum sensor (LI-191SA sensor, LICOR) and a pyranometer (NR-01, Hukseflux), respectively.

During the period between July, 2013 to October, 2014 average intensity of incoming solar radiation during the daytime hours (0800 hr to 1600 hr IST) stood at 609 Wm^{-2} whereas that of PAR (Photosynthetically Active Radiation) was 201 Wm^{-2} and the overall half-hourly average value of climatic efficiency

(PAR:Insolation) was 0.35. Half-hourly values of climatic efficiency ranged between 0.19 and 0.66. Mean values of climatic efficiencies at half-hourly intervals are plotted in figure15.

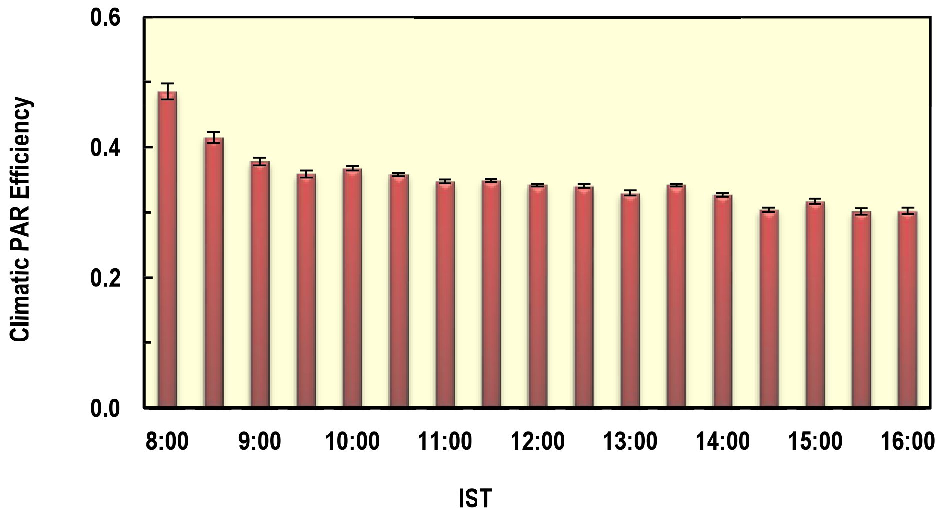


Fig. 15. Diurnal dynamics of PAR : Insolation ratio

At this location, irrespective of months or seasons, the proportion of PAR in instantaneous insolation seemed to be slightly higher during the morning hours till 1030 AM, stabilized to a lower value thereafter and often reached the minimum values in the late afternoon hours. Much higher variations in the ratio value were found in the sunrise and sunset hours (data not shown here) and in cloudy instances under the diffuse light environment. The magnitude of mean diurnal variation in the ratio value was relatively lower during the post-monsoon (October-November) season compared to the others. Similarly, when different sections of the day were considered, it was found that during the morning hours period, average climatic efficiency was lower in the post-monsoon season than that of others. For other sections of the day, no appreciable differences could be noticed among seasons.

The seasonal mean for climatic efficiency was highest in the monsoon season followed by summer, winter and the least in post-monsoon season (Table 8). For the main crop growing seasons, viz. *kharif* (June-September) and *rabi* (November-March), the mean values were 0.36 and 0.33, respectively and the annual mean stood at 0.35.

Average diurnal pattern of climatic efficiency for various seasons of the year are presented graphically in figure 16 and the detailed monthly statistics are provided in Appendix-IV.

Table 8. Seasonal and annual dynamics of PAR : Insolation ratio during different time periods of the day

Season	Morning (08:00-10:30 hr)	Mid-day (11:00-14:30 hr)	Afternoon (15:00-16:00 hr)	Mean (08:00-10:30 hr)
Monsoon	0.42	0.34	0.31	0.36
Post-Monsoon	0.31	0.33	0.33	0.32
Winter	0.40	0.33	0.29	0.34
Summer	0.41	0.34	0.30	0.35
Annual	0.41	0.34	0.31	0.35

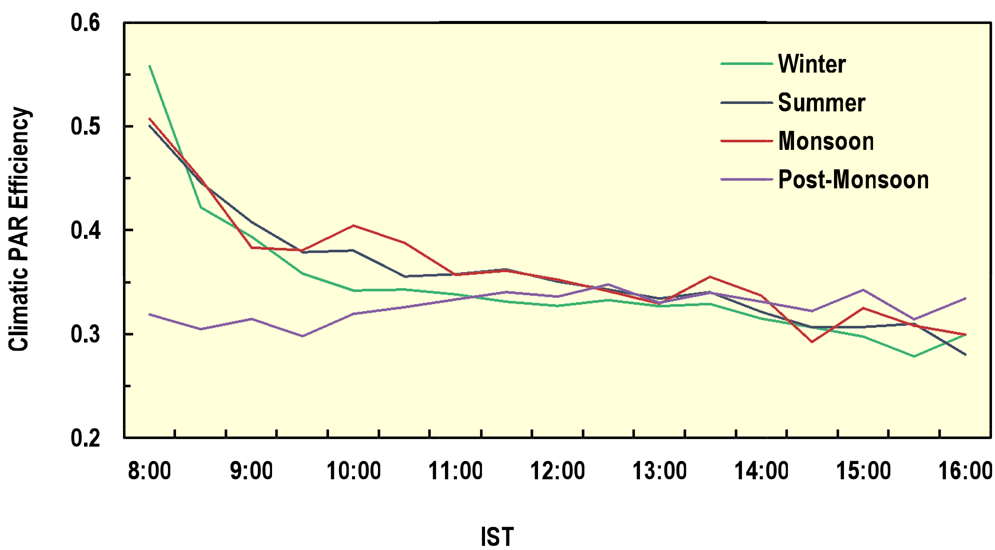


Fig.16. Diurnal dynamics of PAR : Insolation ratio in four different seasons

9. Wind Patterns

Features of wind flow, viz. average directional frequency and or speed at any place are often represented in the form of graphic diagrams. Such types of diagrams are referred to as wind roses and useful for quick assessment of the wind situation. In measuring GHG fluxes from the agricultural field, alignment of sensors as per prevailing wind directions is necessary to ensure that the flux footprint are well within the target crop area. The mean wind direction of a location does not change but there could be considerable interannual variations in the frequency of wind from different directions.

Monthly wind rose diagrams for the years 2012 and 2013 that witnessed large differences in rainfall, have been prepared using data recorded by an automatic weather station (AWS) at NIASM site. A sonic windspeed/wind direction sensor (85000, RM Young), placed at 3 meter height on the tower, recorded observations at a two minute interval and half-hourly average values were stored in a datalogger (H-500 XL, Water Log) (Appendix-V). During the southwest monsoon season (June-September), frequency of wind flow from west of south west, south west, south of south west and south directions were altogether higher by 12.4 % in 2013 (monsoon rainfall: 494 mm) than that in 2013 (monsoon rainfall: 200 mm). Monsoon (SW) season wind patterns for the year 2012 and 2013 are given in the figure 17.

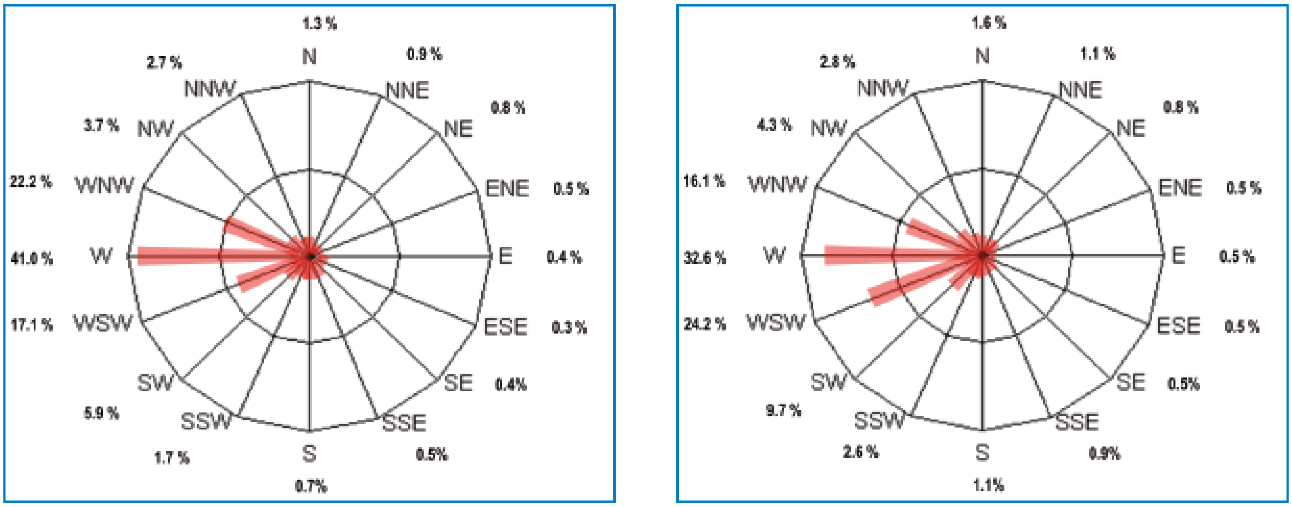


Fig. 17. Comparison of SW monsoon season wind roses of two contrasting years

In case of wind speed, during the year 2014, monthly average values have been found to vary between 4.5 (December) and 12.4 km h^{-1} (July) and the annual average stood at 7.3 km h^{-1} (Fig. 18).

10. CO_2 Exchange at Crop-Atmosphere Interface

Some gases, though occur in traces (<1% of the atmosphere), control heat regulation of earth through their selective absorption of long wave radiation and reradiating it back towards the earth surface. These are known as the greenhouse gases (GHGs). Greenhouse gases include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone and halocarbons. Increased concentrations of the GHGs in the earth's atmosphere are influencing the natural carbon balance of terrestrial ecosystems, leading to an increase in the average temperature of the earth's surface and many perceptible and undesirable changes in climate (IPCC, 2001). Thus, reliable and intensive monitoring of GHGs are necessary for better prediction of climate change and its feedback on the vegetation production system, regionally and globally. Eddy covariance (EC) technique is widely employed as a standard method to monitor GHG fluxes (Aubinet et al., 2000). It is a micro-meteorological technique that provides direct and continuous measurements of net upward or downward movement of energy and gases. The flux data thus obtained provides true representation of an ecosystem as it gives an area integrated measure and used in the flux aggregation scheme from ecosystem to regional scale along with aircraft or satellite based measures. Diurnal and seasonal dynamics of CO_2 fluxes (also termed as net ecosystem exchange, NEE) in relation to agricultural crops are being monitored at NIASM farm at Baramati. Two legumes, *viz. dhaincha* and soybean and cereal crop wheat have been monitored so far. *Dhaincha* was grown as a rainfed crop and both wheat and soybean were raised under irrigated conditions.

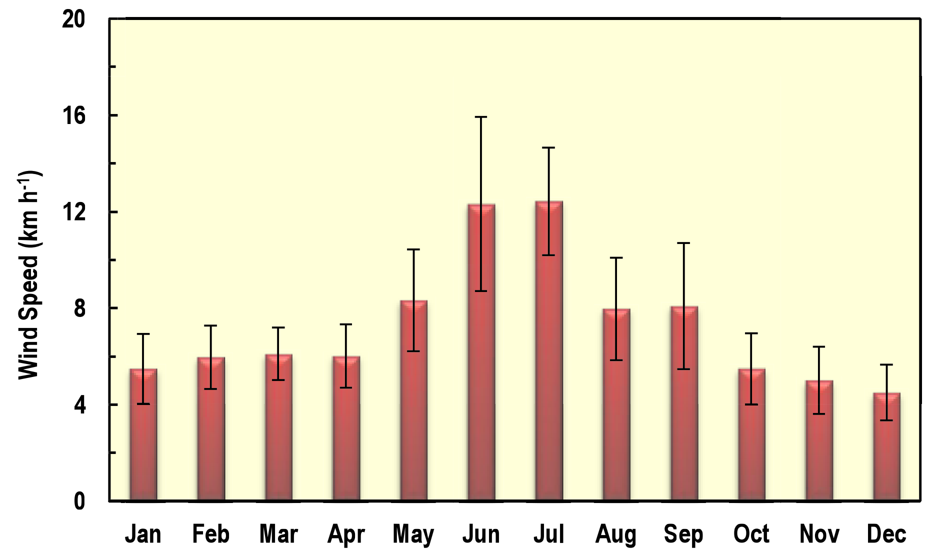


Fig. 18. Monthly average wind speed in a year (2014)

CO_2 exchange characteristics of the above crops were investigated in relation to various biophysical variables and environmental conditions during the growing season.

10.1 Eddy covariance technique

Open path eddy covariance system was installed in the south side research farm in August, 2013. Three-dimensional (3-D) wind speed and temperature were measured using a 3-D sonic anemometer (CSAT3, Campbell Scientific) and open path type infrared gas analyser (EC-150, Campbell Scientific) was used to measure the fluctuations in CO_2 and water vapour densities. The above two sensors had a physical separation (mid-axis distance) of only 2 cm. Apart from these two fast response sensors that are actually used to measure the net exchanges of CO_2 and H_2O using the eddy covariance technique, the tower was also equipped with a host of slow response research grade sensors required for monitoring of energy balance and micrometeorological conditions near the crop. These include one four component net radiometer (NR01, Hukseflux), two soil heat flux sensors (HFP01, Hukseflux), two soil moisture sensors (CS616, Campbell Scientific), two soil temperature sensors (TCAV, Campbell Scientific) and one senor for ambient temperature (HMP155A, Campbell Scientific) measurement.

The CO_2 fluxes measured by the eddy covariance system represent the net CO_2 exchange rate between the crop surface and the overlying atmosphere. As all the crops studied here were of fairly short height (<3 m), CO_2 storage profile within the plant canopy was negligible and hence not undertaken. The system measured all the parameters diurnally i.e. for the entire 24-hours period and continued without any break throughout the season. The mean vertical flux density of CO_2 (Fz) obtained as covariance between vertical wind fluctuations (w) and the CO_2 mixing ratio (c) was averaged at 30 minutes interval (Baldocchi, 2003).

$$Fz = \bar{a} + \overline{w'c'}$$

Where, "a" refers to air density, the over bars denote time averaging and the primes represent fluctuations from average value. Flux sign convention followed by the atmospheric physicists and micrometeorologists was adopted i.e. a positive flux indicating net CO_2 transfer into the atmosphere and a negative one infers net downward movement of CO_2 towards the vegetation and soil surface.

The raw data for flux computations was sampled at 10 Hz frequency using a programme in-built in the data logger that performed all the processing online and in real time. It also applied density corrections on the measured CO_2 fluxes by following the WPL (Webb-Pearman-Leuning)-procedure (Webb et al., 1980). WPL-term correction is used to compensate for the fluctuations of temperature and water vapour that affect the measured fluctuations in CO_2.

Half-hourly time series flux data acquired during each crop season was put to rigorous screening by adopting stringent quality control criteria. Suspicious values were first removed by checking datalogger diagnostics. This is followed by removal of spikes, data acquired during periods of stable atmospheric condition, rain events, poor signal strengths and fluxes associated with eddies that are disturbed by the tower hardware infrastructure when it comes from an area lying just at the back of the EC-150 and CSAT-3 sensors. Energy balance closure of the site was also checked to validate the measured fluxes. The screened dataset was then divided into daytime and nighttime periods with day representing the time between 0630 AM to 0600 PM whereas night time flux of a given date was represented by the period between 0630 PM of that date and 0600 AM of the next calendar date. In order to retain only the best quality of data, daytime and nighttime periods were further divided based on generally observed variations, each into sections comprising of few consecutive hours (4 hours for day and six hours for night) and checked for distributional symmetry. Five days moving average interpolation method was used to fill gaps in the screened datasets. A few unrealistic flux values possibly arising out of wind convergence were also replaced and gaps were filled using the aforesaid moving average method. Various statistics were then calculated on these reconstructed data set susing Microsoft Excel software and sample footprint analysis were done using eddy pro software.

10.2 Monitoring CO_2 flux dynamics

During the time of flux monitoring adequate footprint area under the same crop around the flux tower was maintained. Crop establishment and management activities in the studied crops were as follows:

Dhaincha: Net exchange of CO_2 from the green manuring crop, *dhaincha* (*Sesbania aculeata*) was studied for the first time. The study was conducted during the monsoon season, 2013 (August to October) with *dhaincha* crop grown in about 2.25 ha of contiguous land area as a rainfed crop and a seed rate of about 40 Kg ha^{-1} was used (Fig. 19).

Wheat: The study was conducted during the *rabi* season, 2013-14 (November to March). A contiguous land area of about 1.5 ha surrounding the eddy covariance tower was sown during November 15-17 with a single variety (HD-2189). In addition, about 1 ha of adjoining farmland area was maintained under wheat crop but with a mixture of varieties (Fig. 20). Maxima for the crop height and leaf area index (LAI) averaged over the footprint area were found to be 85.2 cm and 4.3, respectively.

Soybean: A contiguous land area of about 1.5 ha surrounding the eddy covariance tower was sown with a single variety of soybean crop

(MACS-450) during last week of July, 2014. In addition, another about 1.0 ha of adjoining farmland area was maintained under different genotypes of soybean (Fig. 21). Changes in crop biophysical variables that are known to influence CO_2 exchange was monitored in 1.5 ha area adjoining the tower. Maxima for the crop height and leaf area index (LAI) averaged over the footprint area were 47.5 cm and 5.5, respectively.

Changes in the crop biophysical variables, *viz*. height and LAI for wheat and soybean during the growing season are presented in figure 22 and 23, respectively.

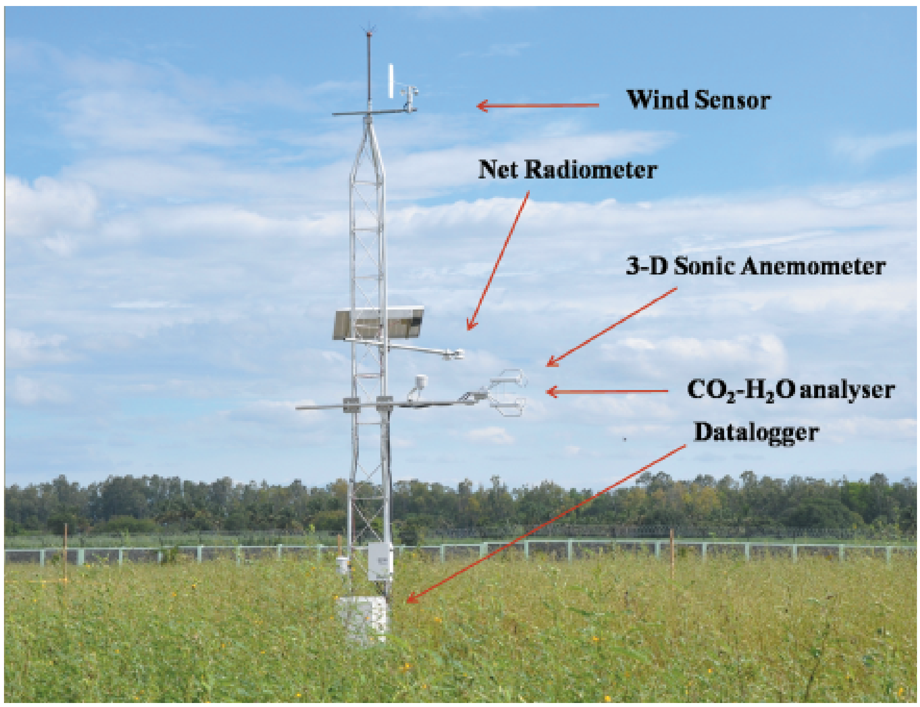


Fig. 19. Monitoring of CO_2 fluxes in *dhaincha* using eddy covariance system

Fig. 20. Monitoring of CO_2 fluxes in wheat using eddy covariance system

Fig. 21. Monitoring of CO_2 fluxes in soybean using eddy covariance system

Dynamics of CO_2 exchanges during the growing seasons of the above three crops are presented in figure 24. Also, various attributes of the datasets and the summary of seasonal flux characteristics of these crops are presented in table 9.

10.3 Net ecosystem exchange

Net assimilation fluxes between -9 and -13 g C m^{-2} d^{-1} have been reported for winter wheat (Baldocchi, 2003; Soegaard et al., 2003; Anthoni et al., 2004; Moureaux et al., 2008; Béziat et al., 2009). The values are similar for rapeseed (Béziat et al., 2009), soybean (Hollinger et al., 2005) and sugar beet (Moureaux et al., 2008). Guo et al. (2013) observed that the daily CO_2 flux was related to crop growth stage, soil temperature and rainfall. Hernandez-Ramirez et al., (2011) observed that under non-limiting soil water availability conditions seasonal variations of CO_2 fluxes were mostly controlled by ambient temperature and available light in corn and soybean. In contrast, with full-developed canopies, available light was the main driver of daytime CO_2 uptake. Similar observation on the relationship between day time NEE and incident light in maize have been reported by Suyker et al. (2004).

Dhaincha: The entire flux (NEE) observation period in *dhaincha* at NIASM could be divided into five distinct phases (study periods I to V) considering both the crop growth and environmental conditions. Average daytime and night time fluxes during each of these periods are presented in table 10. It was observed that both the daytime and nighttime fluxes showed highest magnitude during the vegetative to flowering phase with no moisture stress and that of lowest during the senescence phase coupled with severe soil moisture stress.

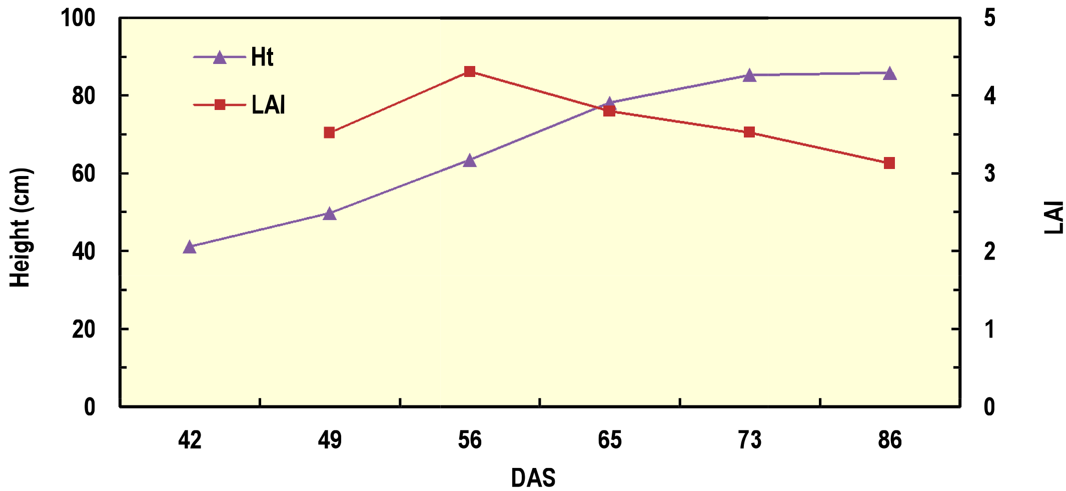


Fig. 22. Seasonal dynamics of crop height and leaf area index of wheat

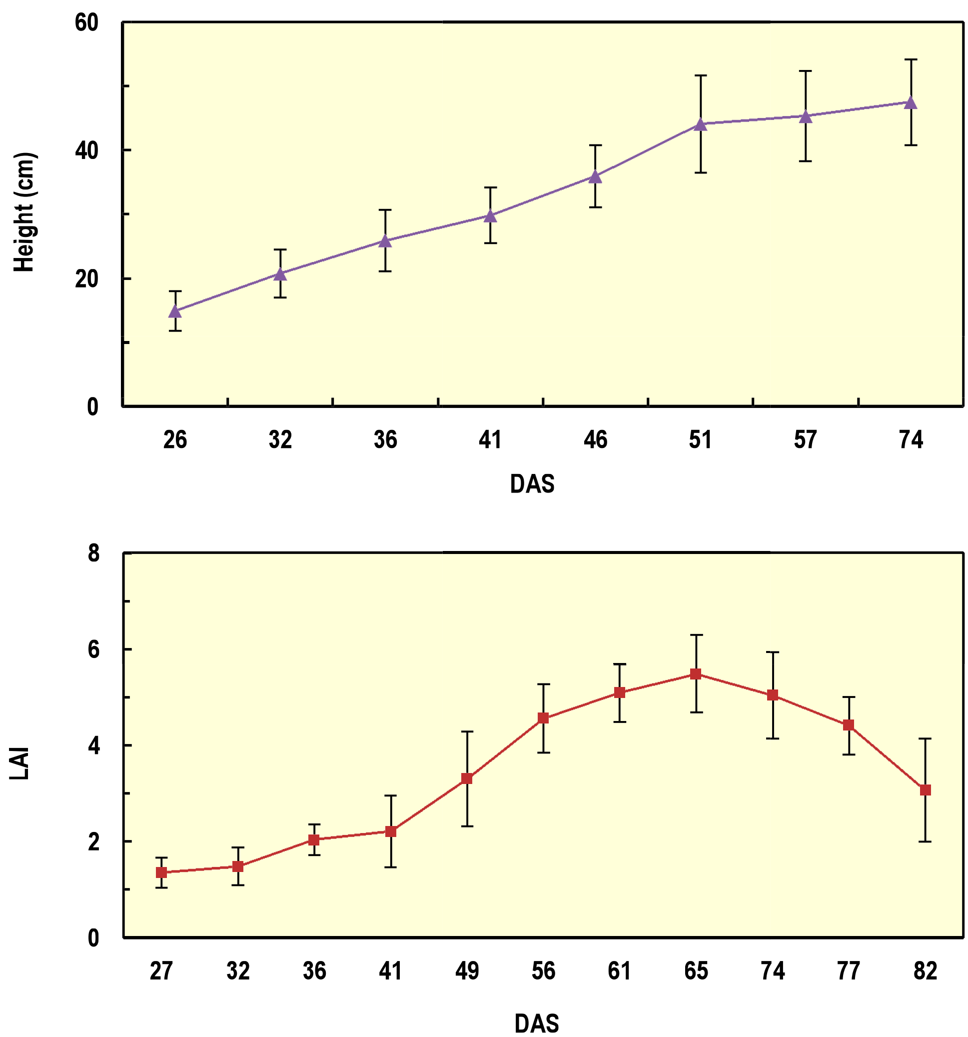


Fig. 23. Seasonal dynamics of crop height and leaf area index in soybean

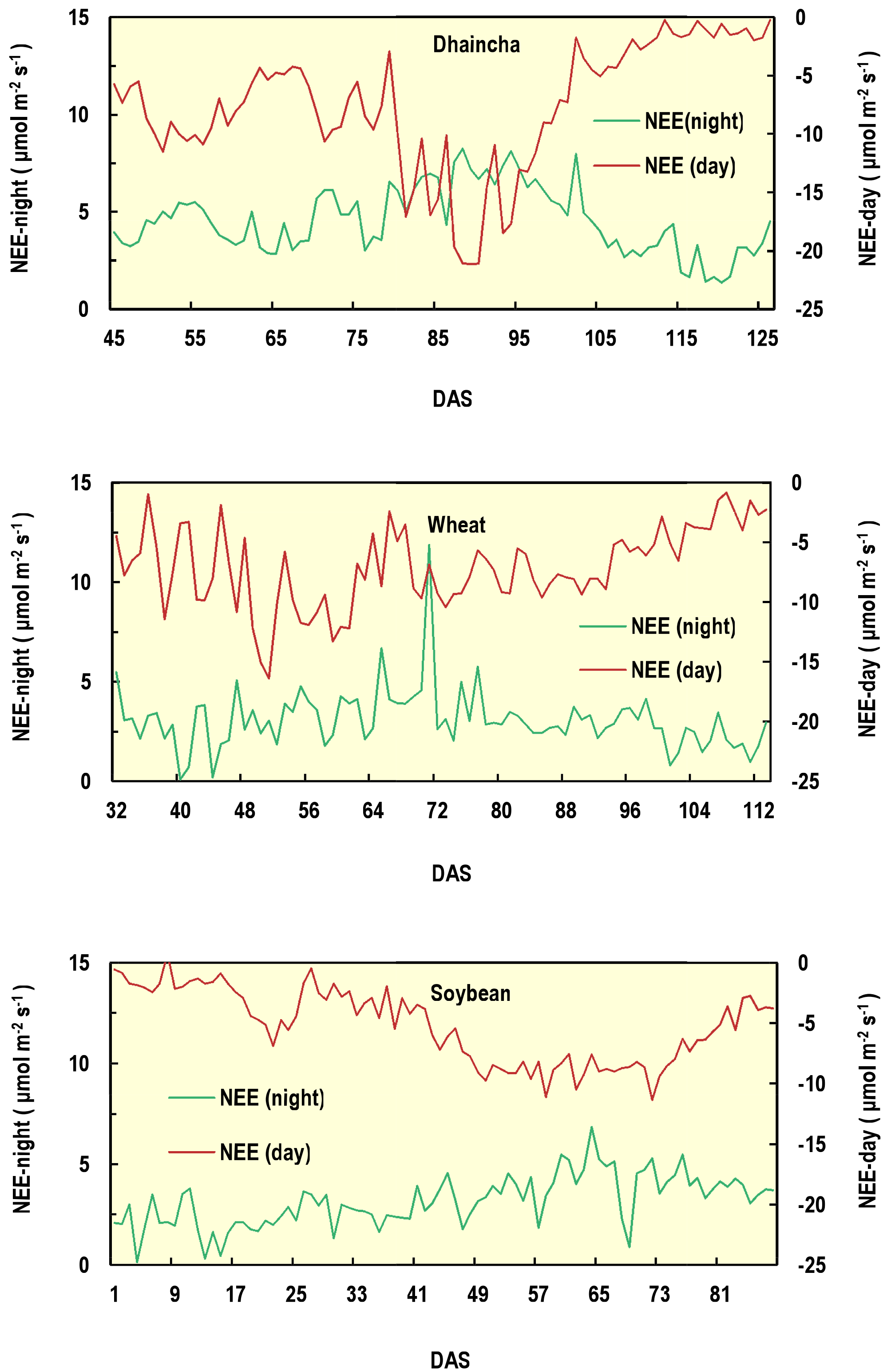


Fig. 24. Temporal dynamics of daytime and night time net ecosystem exchange rate of CO_2 during the growing season of crops

Table 9. Seasonal statistics of net ecosystem exchange (NEE) of CO_2 from various agricultural crops

Dataset Attributes & Flux Characteristics	*Dhaincha*	Wheat	Soybean
Half-hourly NEE datapoints in the time series	n = 4296	n = 3882	n = 4205
Suspicious NEE values (major sources) Datalogger diagnostics warning Low frictional velocity of wind (0.1 ms^{-1}) Backwind fluxes	 6.8 % 8.4 % 30.8 %	 2.4 % 46.8 % 25.2 %	 7.6 % 29.0 % 6.5 %
NEE datapoints retained	n = 2867 (66.7 %)	n = 1206 (31.1 %)	n= 2393 (57 %)
Flux observation period	9-Aug to 29-Oct13	18-Dec13 to 9-Mar14	25-Jul 13 to 20-Oct14
Seasonal CO_2 flux statistics of NEE (μmol m^{-2} s^{-1}) Daytime rate Nighttime rate Estimated net uptake rate	 -7.6 4.6 -1.5	 -7.1 3.1 -2.0	 -5.2 3.2 -1.0

Daily rate of NEE during the aforesaid period varied between 3.1 and -7.2 µmol m^{-2} s^{-1} and the mean stood at -1.5 µmol m^{-2} s^{-1} .

To elucidate the role of environment in controlling NEE, statistical relations between daytime averages NEE and five environmental factors were worked out and presented in table 11. It was observed that during study period I when the crop was still growing and canopy vigour was reduced due to intermittent stress developed due to low rain and very poor water holding capacity of the soil, no single environmental variable could adequately explain the variations in daytime NEE. During study period II when the crop had already attained its maximum canopy growth and there was optimum soil moisture on account of good rain, net radiation, insolation i.e. solar radiation and ambient temperature, all of these factors alone could explain 45-47 % of variations in NEE. It was also observed that daytime ambient temperature upto about 29°C had favoured higher carbon assimilation during the aforesaid period. During study period III when the crop was rapidly shifting to senescence phase due to its age and onset of moisture stress, soil moisture and soil temperature alone could explain 92 % and 75 % of variability in NEE, respectively. During the study period IV, when most of the *dhaincha* plants in the footprint area were into senescence and the soil mostly dry with a few rain events, soil moisture and soil temperature again played important roles as these regulated the soil respiration process which assumed higher importance than photosynthesis and explained about 90 % and 59 % variations in NEE, respectively. When data corresponding to the entire flux observation period i.e. between 45-126 days after sowing (study period V) were pooled together, it was found that soil moisture, soil temperature, net radiation and insolation showed significant correlations with the daytime NEE.

Wheat: Net ecosystem exchange rate during the daytime hours, computed on a daily basis ranged between -0.8 µmol m^{-2} s^{-1} and -16.4 µmol m^{-2} s^{-1} and its seasonal mean stood at -7.1 µmol m^{-2} s^{-1}. Daytime average value of NEE during the vegetative phase of wheat was found to be -9.4 µmol m^{-2} s^{-1} in contrast to the reproductive phase when it was -6.2 μmol m^{-2} s^{-1}. Continuous canopy growth aided by irrigations at regular intervals and top dressing of nitrogenous fertilizer resulted in an increasing trend of daytime CO_2 fluxes during the vegetative period. During the time when daytime carbon capture took place at its maximum rate, footprint average crop height and leaf area index were found to be about 78.1 cm and 3.8, respectively. In the reproductive phase, flowering onwards net CO_2 uptake started declining gradually and during the senescence phase that occurred during the first week of March, 2014 average daytime flux value sharply reduced to a value as low as – 2.08 μmol m^{-2} s^{-1}.

During the vegetative phase of wheat, insolation, net radiation, soil moisture and soil temperature were found to strongly control the daytime carbon uptake rate, the values of correlation coefficient (r) being 0.53, 0.62, 0.84 and 0.72, respectively and all bearing statistical significance ($p < 0.05$). On the other hand, during the reproductive phase it was not radiation but the availability of soil moisture (r = 0.53, $p < 0.01$) that exercised higher control on crop carbon uptake in the typical shallow soil of the NIASM farm. While higher ranges of soil and ambient air temperatures and vapour pressure deficit were negatively associated with crop carbon uptake rate, higher amount of insolation, net radiation and soil moisture had favourably influenced the carbon gain in variable degrees. In the later part of the

Table 10. Daytime and nighttime averages of CO_2 flux (Net Ecosystem Exchange, NEE) during various phenophases and stress conditions in the *dhaincha* ecosystem (Saha et al., 2014)

Time Period	Study Period	Description of the crop ecosystem condition	NEE (μmol m^{-2} s^{-1})	
			Night time	Day time
09-Aug to 08-Sep	I	Vegetative phase	4.2	-7.6
09-Sep to 20-Sep	II	Vegetative to flowering phase	5.5	-11.9
21-Sep to 29-Oct	III	Rapid phase transition to Senescence	4.5	-6.2
27-Sep to 29-Oct	IV	Senescence phase	4.0	-4.0
09-Aug to 29-Oct	V	Seasonal Pool	4.5	-7.6

Table 11. Coefficient of determination (R^2) for daytime NEE in *dhaincha* with respect to various environmental parameters

Environmental Parameters	09-Aug to 08-Sept (n = 31)	09-Sept to 20-Sept (n = 12)	21-Sept to 29-Oct (n = 39)	27-Sept to 29-Oct (n = 33)	09-Aug to 29-Oct (n = 82)
Net Radiation	NS	0.47*	0.34**	0.35**	0.25**
Insolation	NS	0.45*	0.22**	0.28**	0.15**
Soil Moisture	NS	NS	0.92**	0.90**	0.44**
Soil Temperature	0.14*	NS	0.75**	0.59**	0.54**
Ambient Temperature	NS	0.45*	NS	NS	NS

* and ** indicate relationship between the variables and NEE are statistically significant at 95 % and 99 % confidence intervals respectively; 'NS' stands for statistically non-significant at 95 % confidence interval; 'n' stands for no. of sample points or days.

reproductive phase and during senescence soil was mostly dry. For this period, soil moisture and soil temperature explained about 57 and 75% of variations in NEE, respectively.

Soybean: Net ecosystem exchange rate during the daytime hours, computed on a daily basis ranged between 0.8 μmol m^{-2} s^{-1} and -11.3 μmol m^{-2} s^{-1} and its seasonal mean stood at -5.2 μmol m^{-2} s^{-1}. In contrast, average night time fluxes on all dates ranged between 0.1 and 6.8 μmol m^{-2} s^{-1} and the mean stood at 3.2 μmol m^{-2} s^{-1}.

At NIASM farm, all the three crops i.e. *dhaincha*, wheat and soybean, going by the rates of net emission and absorption acted as CO_2 sinks with seasonal average net uptake rates of 1.5, 2.0 and 1.0 μmol m^{-2} s^{-1}, respectively.

11. References

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Annual temperature extremes and frequency of daily maximum and minimum temperatures crossing some threshold temperatures

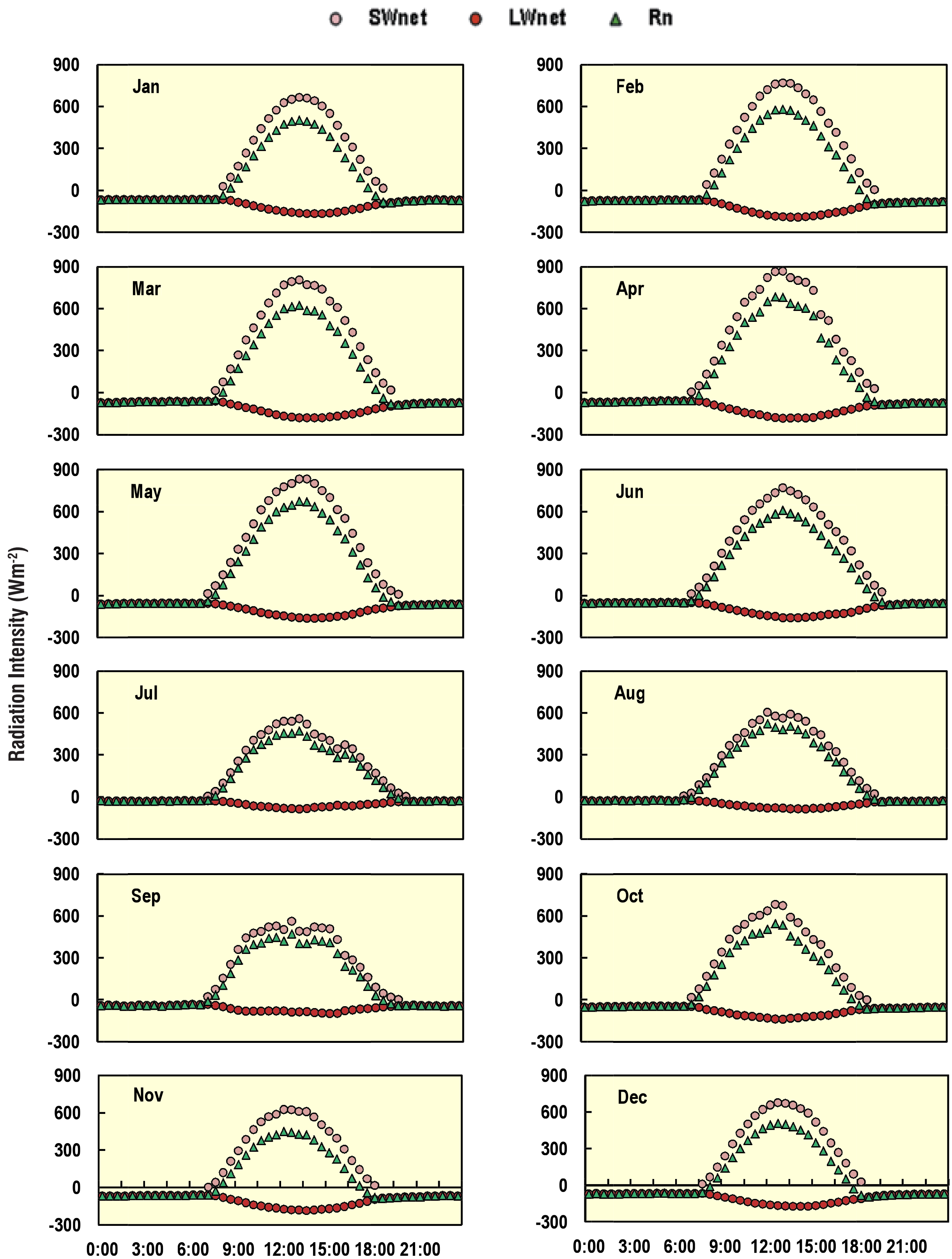
Years	Annual Extremes		Frequency of Daily Max T (°C)					Frequency of Daily Min T (°C)									
	Max T (°C)	Min T (°C)	> 40	> 41	> 42	> 43	> 44	< 15	< 14	< 13	< 12	< 11	< 10	< 9	< 8	< 7	< 6
1986	42	11	17	3	0	0	0	31	14	11	2	0	0	0	0	0	0
1987	35	9	0	0	0	0	0	28	21	5	2	1	1	0	0	0	0
1988	41	11	2	0	0	0	0	21	7	5	1	0	0	0	0	0	0
1989	42	11	5	2	0	0	0	39	24	11	4	0	0	0	0	0	0
1990	42	10	13	5	0	0	0	29	12	4	1	1	0	0	0	0	0
1991	42	9	39	6	0	0	0	39	33	21	9	3	2	0	0	0	0
1992	42	9	39	16	0	0	0	47	32	18	10	6	2	0	0	0	0
1993	44	10	37	20	5	1	0	37	16	10	7	3	0	0	0	0	0
1994	43	9	17	5	2	0	0	53	33	25	13	6	2	0	0	0	0
1995	42	10	5	3	0	0	0	62	36	25	18	5	0	0	0	0	0
1996	44	12	20	11	3	1	0	68	16	1	0	0	0	0	0	0	0
1997	42	10	4	1	0	0	0	11	2	2	2	2	0	0	0	0	0
1998	43	11	42	9	1	0	0	12	10	7	4	0	0	0	0	0	0
1999	42	13	25	5	0	0	0	32	4	0	0	0	0	0	0	0	0
2000	43	13	23	17	8	0	0	14	4	0	0	0	0	0	0	0	0
2001	44	8	28	16	5	3	0	59	44	32	20	17	8	1	0	0	0
2002	43	9	30	17	5	0	0	96	82	63	39	20	11	0	0	0	0
2003	45	9	21	12	1	1	1	73	55	37	20	15	4	0	0	0	0
2004	45	8	35	22	7	2	1	84	66	51	40	30	11	2	0	0	0
2005	43	7	15	7	2	0	0	104	94	65	48	41	24	8	4	0	0

Years	Annual Extremes		Frequency of Daily Max T (°C)					Frequency of Daily Min T (°C)									
	Max T (°C)	Min T (°C)	> 40	> 41	> 42	> 43	> 44	< 15	< 14	< 13	< 12	< 11	< 10	< 9	< 8	< 7	< 6
2006	42	5	26	15	0	0	0	93	73	68	54	38	16	7	5	3	2
2007	42	7	36	6	0	0	0	110	95	76	45	27	7	5	4	0	0
2008	42	6	30	12	0	0	0	93	71	49	39	35	22	4	2	1	0
2009	43	8	27	21	2	0	0	82	59	36	17	10	2	1	0	0	0
2010	43	8	47	28	2	0	0	52	39	32	28	17	13	7	0	0	0
2011	39	7	0	0	0	0	0	93	84	80	45	34	15	8	4	0	0
NIASM																	
2013	41.4	8.5	14	3	0	0	0	52	39	27	17	14	10	3	0	0	0
2014	40	7	0	0	0	0	0	82	61	50	34	19	8	5	3	0	0

Weekly rainfall distribution and dependable rainfall

Standard Meteorological Weeks (W)	Week ending on	Long-term average rainfall (mm)	Dependable Rainfall (mm) (at different probabilities)				
			10 %	25 %	50 %	75 %	90 %
1	7-Jan	0.5	2.8	2.0	1.2	0.7	0.4
2	14-Jan	0.3	2.3	1.7	1.2	0.7	0.5
3	21-Jan	0.1	1.4	1.2	1.1	0.9	0.7
4	28-Jan	0.0	1.6	1.3	0.9	0.7	0.5
5	4-Feb	0.0	0.0	0.0	0.0	0.0	0.0
6	11-Feb	0.0	2.3	1.7	0.0	0.3	0.0
7	18-Feb	0.0	2.3	1.7	0.0	0.3	0.0
8	25-Feb	0.2	3.3	2.3	0.2	0.2	0.0
9	4-Mar	0.9	4.3	2.7	1.4	0.6	0.2
10	11-Mar	1.4	5.3	3.3	1.7	0.7	0.3
11	18-Mar	1.2	4.9	3.0	1.6	0.7	0.3
12	25-Mar	0.6	3.4	2.2	1.3	0.7	0.3
13	1-Apr	0.6	3.2	2.1	1.3	0.7	0.4
14	8-Apr	1.8	6.7	3.9	1.8	0.7	0.2
15	15-Apr	1.5	5.6	3.4	1.7	0.7	0.3
16	22-Apr	0.5	3.0	2.1	1.3	0.7	0.4
17	29-Apr	1.5	5.8	3.5	1.7	0.7	0.3
18	6-May	2.1	7.3	4.3	2.0	0.8	0.3
19	13-May	1.9	6.7	4.0	2.0	0.8	0.3
20	20-May	16.6	49.7	22.2	6.3	1.0	0.1
21	27-May	11.6	33.8	16.7	5.9	1.4	0.2
22	3-Jun	19.4	53.0	27.7	10.7	2.9	0.6
23	10-Jun	31.4	81.2	44.5	18.9	6.0	1.5
24	17-Jun	36.4	96.4	51.0	20.3	5.8	1.3
25	24-Jun	22.1	60.1	31.4	12.2	3.4	0.7
26	1-Jul	12.2	33.5	18.1	7.5	2.3	0.6

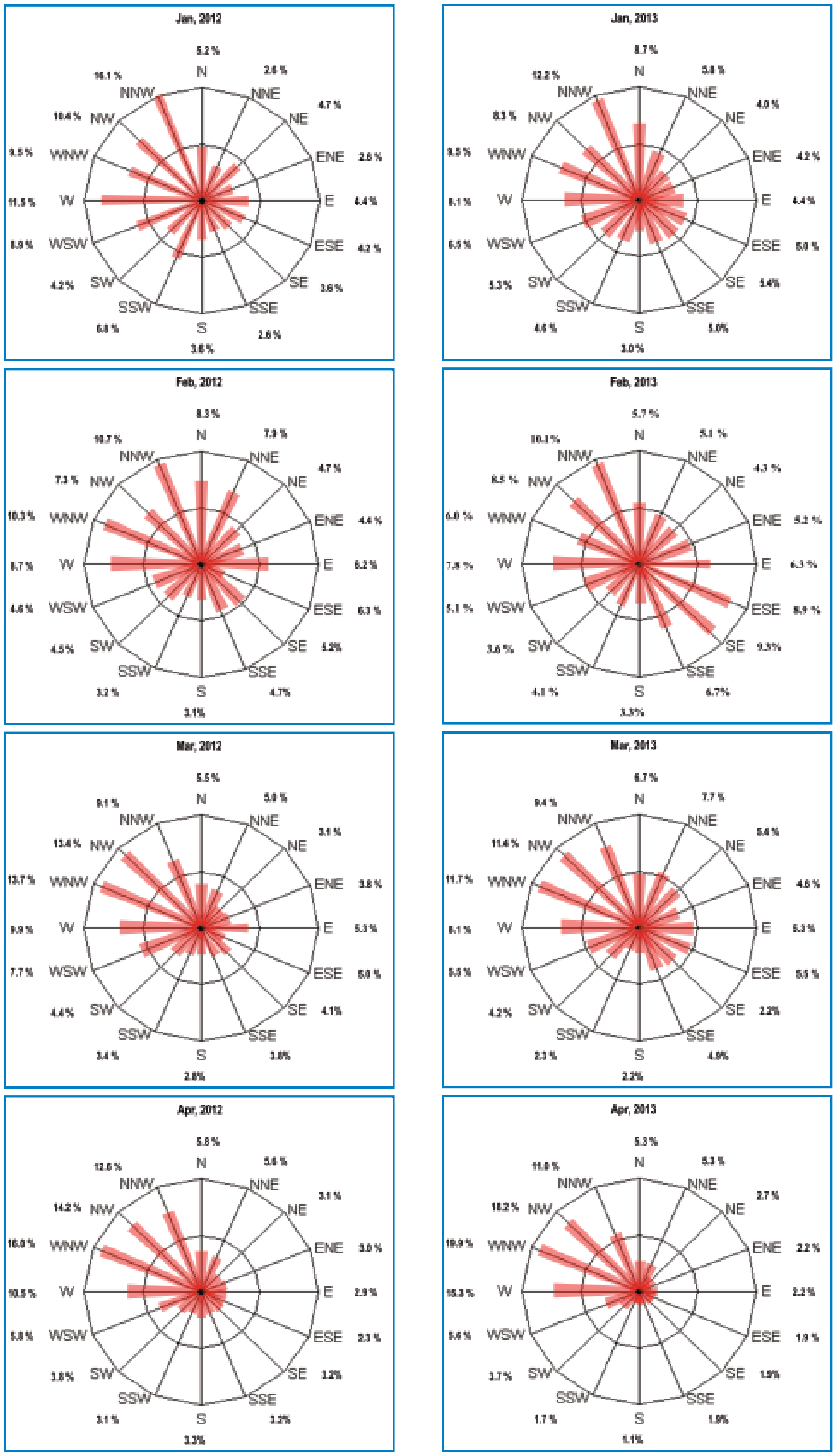
Standard Meteorological Weeks (W)	Week ending on	Long-term average rainfall (mm)	Dependable Rainfall (mm) (at different probabilities)				
			10 %	25 %	50 %	75 %	90 %
27	8-Jul	11.7	31.3	17.5	7.7	2.6	0.7
28	15-Jul	13.8	36.4	20.4	9.0	3.1	0.9
29	22-Jul	20.4	53.7	29.4	12.4	4.0	1.0
30	29-Jul	14.2	37.3	21.0	9.3	3.2	0.9
31	5-Aug	15.3	41.1	22.4	9.5	3.0	0.8
32	12-Aug	18.0	50.8	25.3	9.0	2.1	0.4
33	19-Aug	9.4	26.4	14.3	5.9	1.8	0.4
34	26-Aug	27.2	75.8	37.5	13.1	3.0	0.5
35	2-Sep	17.0	45.7	24.6	10.1	3.0	0.7
36	9-Sep	25.8	71.3	35.9	13.1	3.2	0.6
37	16-Sep	42.4	113.4	58.7	22.4	6.0	1.2
38	23-Sep	39.2	100.5	55.3	23.7	7.7	2.0
39	30-Sep	43.3	110.3	61.0	26.3	8.6	2.3
40	7-Oct	47.2	123.8	65.7	26.3	7.6	1.7
41	14-Oct	27.5	78.3	37.1	12.0	2.4	0.3
42	21-Oct	21.2	60.2	29.3	10.0	2.2	0.3
43	28-Oct	7.9	24.1	11.8	4.1	0.9	0.1
44	4-Nov	1.9	7.0	4.0	1.8	0.7	0.2
45	11-Nov	4.4	13.3	7.4	3.2	1.1	0.3
46	18-Nov	5.8	17.9	9.1	3.4	0.9	0.2
47	25-Nov	1.7	6.0	3.7	1.9	0.9	0.3
48	2-Dec	1.2	4.9	3.0	1.5	0.6	0.2
49	9-Dec	4.3	14.1	7.0	2.5	0.6	0.1
50	16-Dec	2.6	9.3	4.9	1.9	0.5	0.1
51	23-Dec	0.1	1.4	1.2	1.1	0.9	0.7
52	31-Dec	0.0	1.6	1.3	0.9	0.7	0.5
Annual		**588**	**884.4**	**719.5**	**561.5**	**428.6**	**329.1**



Average diurnal trend of net radiation and its shortwave and longwave components for different months of the year

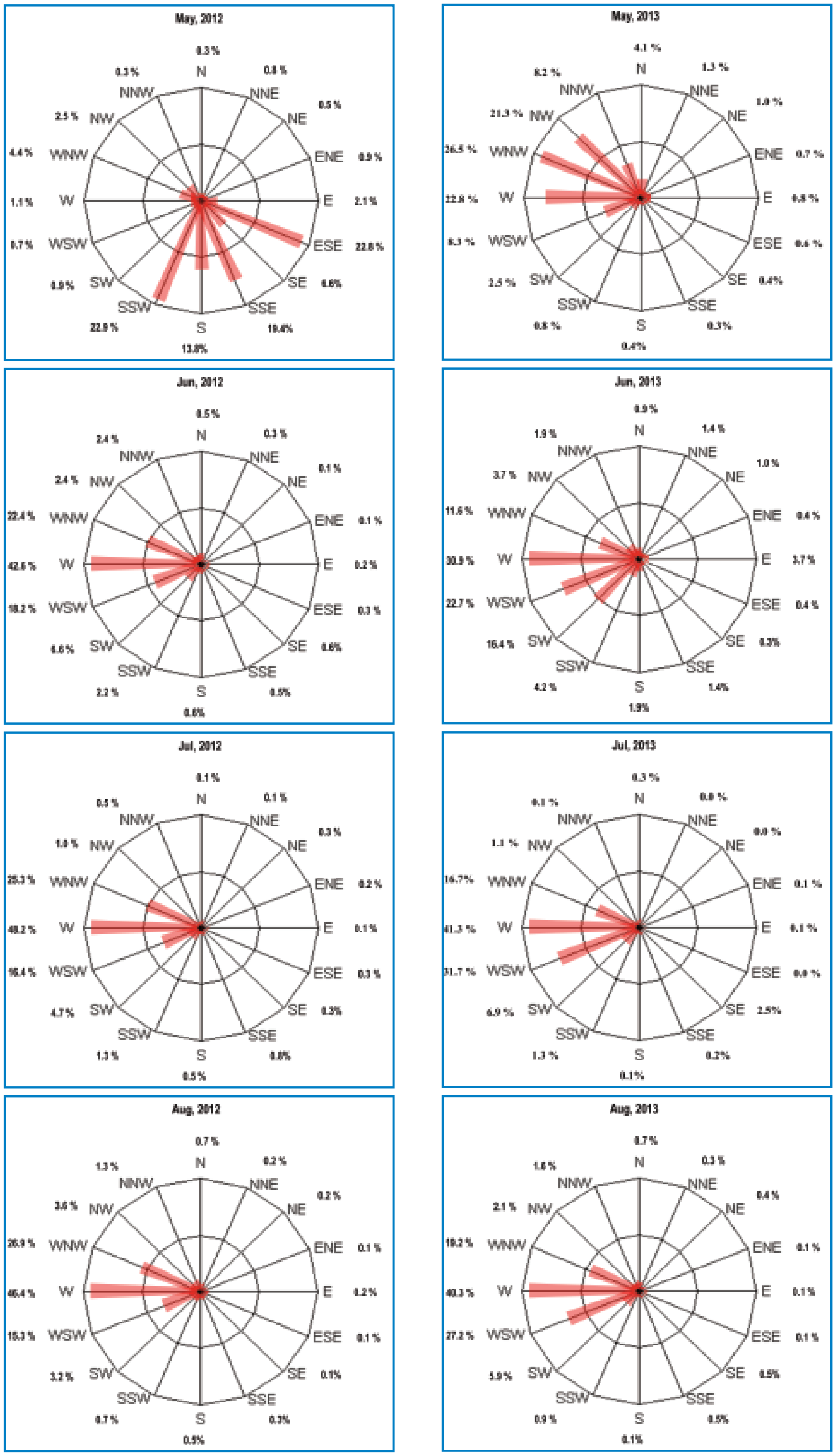
Half-hourly statistics of PAR: Insolation ratio during the diurnal cycle for different months of a year

Time	Jan	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Max	Min	Mean
08:00	0.62	0.66	0.53	0.47	0.60	0.64	0.55	0.23	0.30	0.34	0.40	0.66	0.23	0.49
08:30	0.43	0.50	0.44	0.45	0.50	0.50	0.56	0.24	0.27	0.34	0.33	0.56	0.24	0.41
09:00	0.42	0.44	0.40	0.42	0.44	0.43	0.42	0.24	0.30	0.33	0.32	0.44	0.24	0.38
09:30	0.37	0.39	0.38	0.38	0.41	0.38	0.48	0.25	0.28	0.32	0.31	0.48	0.25	0.36
10:00	0.34	0.38	0.38	0.38	0.39	0.40	0.44	0.40	0.35	0.29	0.31	0.44	0.29	0.37
10:30	0.35	0.37	0.35	0.36	0.40	0.38	0.37	0.40	0.34	0.31	0.31	0.40	0.31	0.36
11:00	0.34	0.36	0.37	0.35	0.34	0.40	0.31	0.38	0.35	0.32	0.31	0.40	0.31	0.35
11:30	0.35	0.34	0.37	0.36	0.39	0.31	0.34	0.40	0.34	0.34	0.31	0.40	0.31	0.35
12:00	0.33	0.34	0.34	0.36	0.38	0.34	0.30	0.38	0.34	0.33	0.31	0.38	0.30	0.34
12:30	0.34	0.35	0.34	0.34	0.35	0.32	0.28	0.42	0.36	0.33	0.30	0.42	0.28	0.34
13:00	0.33	0.33	0.33	0.34	0.31	0.28	0.27	0.46	0.34	0.32	0.32	0.46	0.27	0.33
13:30	0.33	0.34	0.33	0.35	0.33	0.39	0.31	0.38	0.35	0.33	0.31	0.39	0.31	0.34
14:00	0.32	0.32	0.33	0.31	0.30	0.27	0.36	0.41	0.35	0.31	0.31	0.41	0.27	0.33
14:30	0.32	0.30	0.31	0.30	0.30	0.26	0.23	0.39	0.35	0.30	0.30	0.39	0.23	0.30
15:00	0.28	0.31	0.29	0.32	0.29	0.33	0.24	0.44	0.36	0.33	0.30	0.44	0.24	0.32
15:30	0.28	0.28	0.31	0.31	0.30	0.24	0.25	0.44	0.35	0.28	0.28	0.44	0.24	0.30
16:00	0.35	0.27	0.28	0.28	0.32	0.30	0.19	0.39	0.36	0.31	0.28	0.39	0.19	0.30
Max	0.62	0.66	0.53	0.47	0.60	0.64	0.56	0.46	0.36	0.34	0.40			
Min	0.28	0.27	0.28	0.28	0.29	0.24	0.19	0.23	0.27	0.28	0.28			
Mean	0.36	0.37	0.36	0.36	0.37	0.36	0.35	0.37	0.33	0.32	0.31			



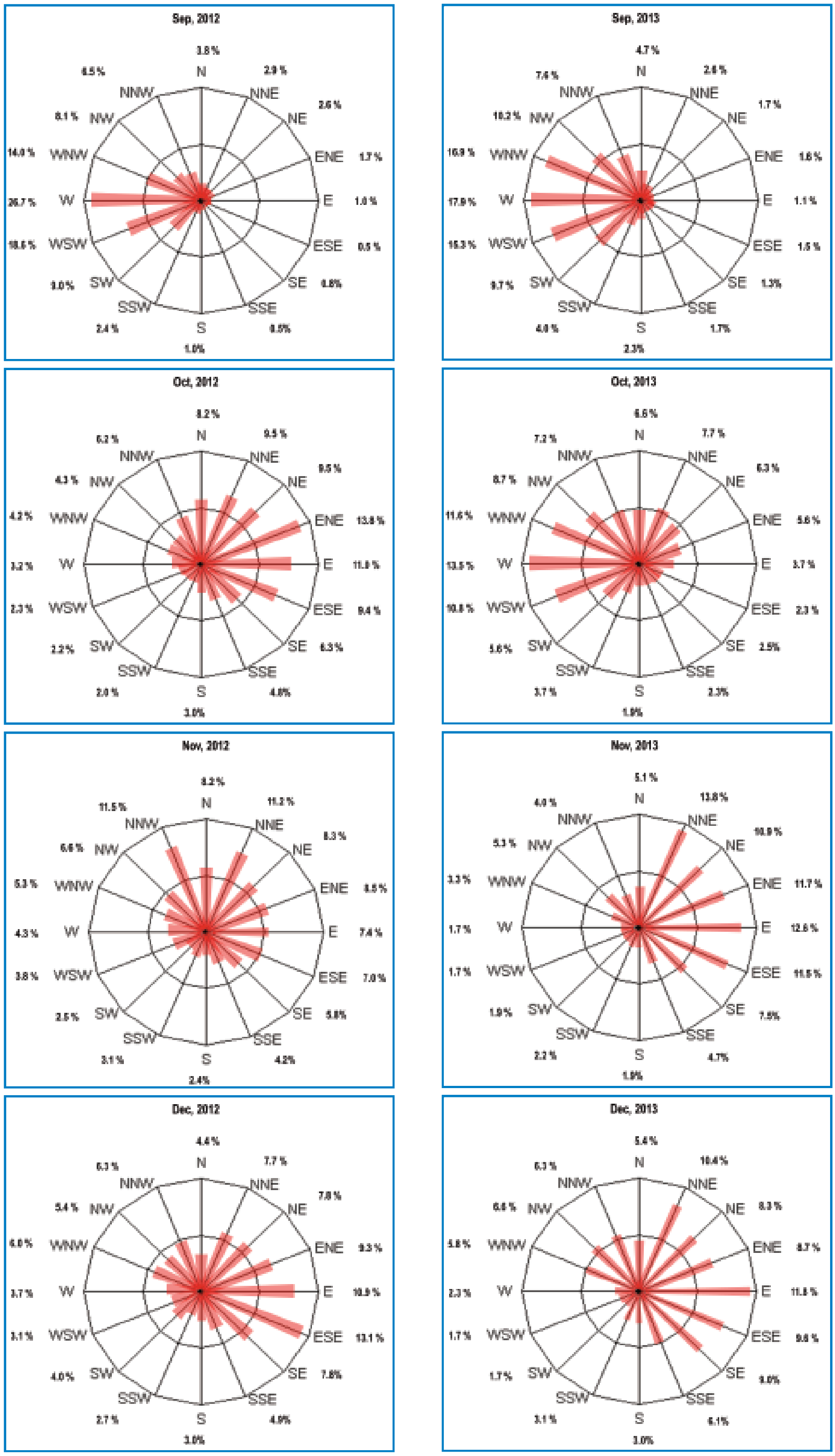
a b

Monthly wind roses (January-April)during 2012 (a) and 2013 (b)



a **b**

Monthly wind roses (May-August) during 2012 (a) and 2013 (b)



a b

Monthly wind roses (September-December) during 2012 (a) and 2013 (b)

Monthly statistics of some weather variables at NIASM agro-meteorological observatory during 2012-2014

Months	Tmax (°C)	Tmin (°C)	T mean (°C)	RHmax (%)	RHmin (%)	RH mean (%)	Rain (mm)	Pan-E (mmd^{-1})
Jan-12	29.8	13.5	21.7	67	23	45	0.0	NA
Feb-12	33.0	15.4	24.2	59	16	38	0.0	NA
Mar-12	36.3	17.3	26.8	57	10	33	0.0	NA
Apr-12	38.3	22.1	30.2	68	14	41	14.3	NA
May-12	38.7	22.1	30.4	76	15	46	14.0	NA
Jun-12	34.3	23.4	28.8	83	38	60	17.3	NA
Jul-12	31.3	23.0	27.1	89	50	70	72.0	6.1
Aug-12	31.1	22.1	26.6	91	51	71	38.3	6.3
Sep-12	30.9	21.5	26.2	94	49	71	72.8	5.8
Oct-12	31.2	20.2	25.7	86	39	62	50.8	5.7
Nov-12	30.9	17.6	24.2	74	31	52	8.8	5.7
Dec-12	30.4	15.7	23.1	73	29	51	0.0	5.1
Annual (2012)	33.0	19.5	26.3	76	30	53	288	NA
Jan-13	31.4	15.1	23.3	67	22	44	0.0	5.8
Feb-13	32.8	17.4	25.1	63	21	42	0.0	6.9
Mar-13	36.1	19.5	27.8	50	13	32	0.0	9.3
Apr-13	38.5	21.4	29.9	62	12	37	0.0	10.7
May-13	38.9	24.3	31.6	69	18	44	0.0	11.1
Jun-13	31.0	22.4	26.7	93	52	73	102.0	7.2
Jul-13	28.0	22.0	25.0	94	66	80	103.0	4.8
Aug-13	30.2	21.3	25.7	92	53	72	14.8	6.4
Sep-13	30.7	20.8	25.8	96	52	74	274.5	6.6
Oct-13	32.1	21.1	26.6	94	43	69	24.3	4.8
Nov-13	30.1	16.2	23.2	86	35	60	1.3	4.4
Dec-13	28.7	12.7	20.7	88	30	59	1.5	3.5
Annual (2013)	32.4	19.5	25.9	79	35	57	521	6.8

Months	Tmax (°C)	Tmin (°C)	T mean (°C)	RHmax (%)	RHmin (%)	RH mean (%)	Rain (mm)	Pan-E (mmd^{-1})
Jan-14	29.0	13.9	21.5	86	33	60	0.0	3.6
Feb-14	30.5	14.0	22.2	80	26	53	0.8	4.8
Mar-14	33.9	17.9	25.9	80	24	52	72.8	6.1
Apr-14	37.5	21.1	29.3	75	16	45	51.8	7.6
May-14	37.1	22.2	29.7	86	22	54	107.8	7.6
Jun-14	34.5	22.9	28.7	89	38	63	84.3	8.2
Jul-14	29.9	22.2	26.0	97	58	78	105.1	5.1
Aug-14	30.0	21.1	25.6	90	66	78	184.7	4.3
Sep-14	30.2	20.6	25.4	87	54	70	75.7	4.6
Oct-14	32.0	19.5	25.7	82	39	61	26.1	5.1
Nov-14	30.3	16.8	23.5	96	38	67	44.0	4.5
Dec-14	28.3	12.3	20.3	96	35	66	7.6	3.6
Annual (2014)	31.9	18.6	25.3	85	38	61	760	5.4

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