

**बोवेन अनुपात ऊर्जा संतुलन विधि का उपयोग करके
सिंचित मक्का-गेहूं में भूतल ऊर्जा प्रवाह**

**Surface Energy fluxes over irrigated maize-wheat
using Bowen Ratio Energy Balance Method**

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Surface Energy fluxes over irrigated maize-wheat using Bowen Ratio Energy Balance Method

A Thesis

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SUNNY ARYA

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CERTIFICATE

This is to certify that the thesis entitled, “**Surface Energy fluxes over irrigated maize-wheat using Bowen Ratio Energy Balance Method.**”, submitted to the Faculty of Post Graduate School, Indian Agricultural Research Institute, New Delhi, by **Mr. Sunny Arya**, Roll No. **20777** in partial fulfillment of the requirements for the award of the degree of **Master of Science in Agricultural Physics**, is a record of bona fide research work carried out by him under my guidance and supervision and that no part of the thesis has been submitted anywhere for the publication or for any other degree or diploma.

I further certify that the assistance and help received during the course of this investigation has been duly acknowledged.

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Dedicated To

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1. INTRODUCTION

Among all other natural resources related to agriculture, water is the prime input (Dugger, 2006). Partitioning of land surface available energy into sensible and latent heat is a basic hydrological process connecting vegetation and atmosphere (Shen *et al.*, 2004). ET links energy partitioning, stomatal conductance, carbon exchange, and water-use efficiency in plant communities, and it serves as a key regulator of ecosystem processes (Woodward and Smith, 1994). Surface energy balance and its partitioning are vital for the regional climate and hydrology, as well as food production and food security (Brown and Halweil, 1998). Therefore, it is crucial to quantify the energy balance components, to understand the different factors and their influence on these terms, their rhythmic change and the monitoring of the evaporative processes over the region. There is a need for a better understanding of the processes controlling ET and the energy partitioning of the entire crop community and also the understanding of the seasonal dynamics, where the phenology of vegetation and variations in soil moisture and temperature plays an important role (Grelle *et al.*, 1999; Viterbo and Beljaars, 1995).

India is facing a serious problem of natural resource scarcity, especially that of water in view of population growth and economic development. India's demand for water is growing at an alarming rate. It currently has the world's second largest population, which is expected to overtake China's by 2050 when it reaches a staggering 1.6 billion, putting increase strain on water resources as the number of people grows (Source: [http:// news.bbc. co.uk/ 2/hi/ 3575994.stm.](http://news.bbc.co.uk/2/hi/3575994.stm), Accessed Date 08.11.2017). A rapidly growing economy and a large agricultural sector will minimize the India's water supply. This problem become a bit more serious for India which has the highest area under irrigation in the world amounting to about 80 – 90% of all water use in India (Shah *et al.*, 2000). Irrigated agriculture even though consume more water but still it is one of the most important factor for poverty alleviation, food security and economic

development in India (Bansil, 2004). As water is our prime input so our aim should be to increase our production with limited water resources.

Management of natural resources needs its proper assessment. In field water balance, one factor is evapotranspiration (ET). ET is the water removed as vapor from the soil plant system by direct evaporation and plant transpiration. It is a component of the hydrological cycle whose accurate calculation at the local and regional scale is needed to achieve an appropriate management of water requirements, in irrigation design and scheduling, watershed hydrology, mechanistic crop growth models and other models that attempt to simulate the soil water budget. The reference evapotranspiration (ET_o) refers to water evaporation from a unit ground area completely covered by a 0.12 m grass, healthy and unstressed and with ample water supply. There are different methods to measure evapotranspiration. Bowen ratio energy balance (BREB) method is a micrometeorological method by combining Bowen ratio with energy balance equation of earth surface (Tanner, 1960). This method has been used to estimate energy (both sensible and latent heat parts) and mass (ET) fluxes to quantify water use of crop (Cargnel *et al.*, 1996 and Elhaddad *et al.*, 2008), calculation of crop coefficients (Malek and Bingham, 1993), evaluate crop water use models (Todd *et al.*, 2000), measurement of emission of trace gases like methane and nitrous oxide etc., from soil or crop surface and to measure carbon dioxide assimilate rate in crops (Chan *et al.*, 1998) and energy balance studies above the crop surface (Hatfield, 1990 and Mokate *et al.*, 1995), BREB method in this respect is very advantageous as it ensure closure of energy balance equation unlike eddy method because it helps in partitioning of available energy into the sensible and latent heat flux using Bowen ratio (Bowen, 1926). Bowen-ratio method closes the energy balance and this leads to the resultant latent and sensible heat fluxes being related to the landscape. (Foken *et al.*, 2008). There has been many, long-term studies of ET based on indirect methods, e.g. water balance, with low time resolution only. However, in order to improve the understanding of ET and energy partitioning processes, high temporal resolution data are essential in many cases. So in present study Bowen ratio energy

balance technique was employed as a tool for measuring the partitioning of available energy into ET and sensible heat fluxes over a maize-wheat crop under irrigated condition with the following objectives:

1. To characterize the micro-meteorological environment of irrigated maize and wheat crops.
2. To estimate surface energy fluxes using BREB (Bowen Ratio Energy Balance) method and relate them to crop growth.

2. REVIEW OF LITERATURE

Agriculture sector is a major consumer of freshwater globally which amounts to about 80% of the total available freshwater (Fischer *et al.*, 2007). Share of freshwater supply to agriculture will continue to decrease with the incessantly increasing competition with urban and industrial water demand (Seckler *et al.*, 1998). Our water consumption pattern and amount will change with time to a much higher value. In developing countries, water demand of industrial sector will increase significantly by 2050. The amount of water available for irrigation will be severely reduced to such a level that our food security itself will be in danger (Rosegrant *et al.*, 2002). According to Vörösmarty *et al.* (2005) about 80% of the total world's population are exposed to high level of threat to water security.

Wheat crop scenario in India for 2015-16 were estimated as 30.23 million hectares in terms of area and 93.50 million tonnes as total production, out of which most of area (93.6%) under wheat crop is irrigated (Agricultural Statistics at a Glance, 2016). It is also one of the most crucial crop in the world and its production increment of about 2% is very essential. This increase is of more importance for developing countries like- South-East Asian countries, to meet demands of ever increasing population and to boost growth in their economy (Reynolds *et al.*, 2008). This is a mammoth task and it is going to be made further complicated by reduced water availability (Shiklomanov & Rodde, 2011) and global warming induced rise in atmospheric temperature (Fischer *et al.*, 2002). Extreme heat (or sensible heat flux) affect the maturing process of wheat senescence and hastens maturity (Lobell *et al.*, 2012). In Indian, maize (*Zea mays*) crop estimated (2015-16) to be grown over an area of 8.69 million hectares out of which 27.2% is irrigated with a total production of 21.18 million tonnes (Agricultural Statistics at a Glance, 2016). So, maize is the third most important food crop in our country after rice and wheat. It has a significant place particularly with wheat as the maize-wheat cropping system which is the third most important cropping system in this country after rice-wheat and rice-rice. (Saad *et al.*, 2015). The yield of maize shows the best positive correlation with evapotranspiration parameter (Payero *et al.*, 2006) and any form of water stress can leads to reduced growth, delayed maturity and reduced crop growth (Denmead and Shaw, 1960).

This problem become a bit more serious for India which has the highest area under irrigation in the world amounting to about 80 – 90% of all water use in India. Out of this 60% of irrigated food production depends on irrigation from groundwater which is depleting fast (Shah *et al.*, 2000). Irrigated agriculture even though consume more water but still it is one of the most important factor for poverty alleviation, food security and economic development in India (Bansil, 2004). On top of all this, phenomenon like climate change which is also accompanied by increased climate vulnerability are likely to have negative effect on sustainability of agriculture ecosystem (Aggarwal, 2008).

Irrigation is not only related to food security and water consumption but also other factors. Adegoke *et al.* (2003), have shown that it can affect regional and local climate. Land cover changes has influence on water vapour flows at planetary scale. Gordon *et al.* (2005) reported that with agriculture area under irrigation has led to increase in global vapour flows by a magnitude of about $2600 \text{ km}^3 \text{ yr}^{-1}$, which is more than twice that of estimated global consumptive irrigation water losses ($\sim 1200 \text{ km}^3 \text{ yr}^{-1}$; Vörösmarty *et al.*, 2005). India has a very large population (about 17.74% of the world's population), which is dependent on monsoon to a great extent, making this country as the perfect place to study interaction among land, human and atmosphere (Gupta *et al.*, 2006). Irrigation has been shown to interact with land and atmosphere with the help of energy exchanges. Irrigated agriculture area (a big part of our country's area), increases the mean vapour fluxes by 17% in comparison to a natural non-irrigated land with a range of 7% (in wet season) to 55% (in dry season) (Douglas *et al.* 2006). Study using Regional Atmospheric Modelling System (RAMS) have also showed that agriculture intensification and irrigation can modify the distribution of energy and soil moisture at the surface. This may cause shift in boundary layer and convergence on a regional scale, convective activities at meso-scale and rainfall over Indian monsoon region. Irrigation was shown to increase the regional latent heat flux which ultimately modifies the available convective potential energy, reduces surface temperature and modifies regional atmosphere circulation pattern. The influence of land use changes on regional condition through modification of energy flux pattern are such great that it needs to be taken into account for accurate weather forecasting (Douglas *et al.* 2009).

There are various ways of evapotranspiration (ET) measurement out of which energy balance is one of the most important one. Initially energy balance method was used to estimate ET at water surface but later on, this concept was applied over cropped

surfaces by Penman (1948) and Budyko (1948) and since then, there is no stopping of it. Evapotranspiration is a very energy intensive process requiring large amount of energy for latent heat of vaporisation. This makes energy balance method as the most common method to estimate latent heat flux and ultimately ET (Jensen & Allen, 2016).

2.1. Energy flux

2.1.1. Micrometeorological methods

Verma (1990) pointed out that there are many micrometeorological methods for measuring mass and energy fluxes at surface like eddy correlation method, gradient based methods, aerodynamic method etc. In the present scenario of climate change, the importance of turbulent heat fluxes like sensible and latent heat flux will keep on increasing. Better understanding the effect of global warming on energy balance changes and the glacier melting will helps us to speculate the effects of global warming (Plüss and Mazzoni, 1994). Ortega *et al.* (1996) reported that even though bulk aerodynamic method were in par with BREB method but using bulk aerodynamic method should be discouraged for complex crop canopy because of the difficulty in measuring the aerodynamic properties of the surface.

For a sparse crop canopy using simple source N95 model, Kustas and Norman (1999) found out that latent heat flux due to soil evaporation tends to be higher than that of transpiration from widely spaced crop plants. Radiative forcing or net radiation in general dominates the high-alpine environment and acts as source of energy during melting of ice (Plüss and Mazzoni, 1994). In this environment turbulent fluxes were also found to be fairly constant across seasons and their relative role as energy source for melting ice were directly proportional to wind speed.

Soil heat flux (G) is one of the fundamental element of the equation dealing with energy balance over land surfaces and to estimate it correctly, we need accurate measurement of flux few centimetres below the soil surface and heat storage term above it (Ochsner *et al.*, 2007). Also while we are calculating G , we also need to take into account storage term for soil, neglecting it will frequently lead to errors that are significant in respect to the soil heat flux. In some situation like that of a dense forest canopy it may be neglected without much repercussions due to it comparatively negligible values in respect to other energy balance components. (Oge'e *et al.*, 2001) The magnitude of G is influenced by various factors like surface cover, soil moisture

content, and solar irradiance. The peak values of soil heat flux in a dry bare soil can reach as high as 300 W m^{-2} . (Fuchs & Hadas, 1972).

Evaporative flux measurement with the BREB method (Bowen, 1926), relies on precise measurement of the amount of energy available for partitioning i.e., $R_n - G$. Decision to omit or consider G value in equation depends on factors like local climate, soil properties, and cropping systems. Neglecting G values in summer or when fluxes need to be calculated for shorter period of time, can lead to overestimation of evapotranspiration. (Simmers, 1977; Kumar & Rao; 1984; Anadranistakis *et al.*, 1996). Even though time derivation of heat capacity requires heat capacity measurements to be taken frequently but still this method yields gives the most accurate soil heat storage data, specifically when soil water content changes rapidly (Ochsner *et al.*, 2007). In soil this component of energy balance is revealed in form of decreasing amplitude of flux with increasing depth and time lag of the sinusoidal pattern wave with depth. Theta probe and heat pulse sensors yield comparable heat capacity values in general (Ochsner *et al.*, 2007). Hourly G for a moist soil beneath a plant canopy, residue layer, or snow cover will be normally lower than $\pm 20 \text{ W m}^{-2}$. It typically represents 1 to 10% of net radiation in an area with actively growing crops (Denmead, 1969; Clothier *et al.*, 1986)

Energy fluxes on the surface can also be calculated using remote sensing. Mallick *et al.* (2010) estimated Bowen ratio from vapour pressure and air temperature data taken from infra-red soundings of the AIRS 5 (Atmospheric Infrared Sounder) sensor. Comparison of estimated flux with thirty surface tower flux values revealed a good agreement between them with no significant bias. Still there are some reservation regarding its accuracy and performance in arid and semi-arid conditions and for best it should be avoided.

2.1.2 Flux network

Realizing the importance of understanding energy fluxes in great detail, a number of coordinated research programs and networks of flux towers has been established such as AMERIFLUX, FLUXNET, EUROFLUX, ASIAFLUX, etc. These serve the purpose of estimation as well as modelling of energy and CO_2 fluxes and to study the functioning and role of terrestrial ecosystems in carbon, water, and energy cycles at various scales for various atmospheric, vegetative and climatic conditions (Irmak, 2010). FLUXNET is a world-wide network of micrometeorological flux

measurement towers (sites) under varied vegetative conditions like, temperate conifer forest, deciduous forest, tropical and boreal forests, grassland, chaparral, wetlands, tundra and crops. (Baldocchi *et al.*, 2001). This will assist in quantification of dynamics and variability of carbon, water, and energy flux densities with time for studying their influence on phenology, droughts occurrence and its frequency, heat spells, El Niño, length of growing period (LGP) etc. (Baldocchi *et al.*, 2001).

There is also an inclusive networks of towers which are BREB system, named as Nebraska Water and Energy Flux Measurement, Modelling, and Research Network (NEBFLUX). As the name suggest, its main function is to measure surface energy fluxes, including actual evapotranspiration, for various vegetation surfaces. (Irmak, 2010). At present, ten BREBSs are operating for long and continuous study of flux over different crop with various treatments like- tilled versus untilled, irrigated and rainfed versus irrigated etc. and different vegetation types as well. It will assists in understanding ecosystem, policy and decision making purposes and devise water conservation measures. Nonetheless, there is an overbearing necessity for these kinds of network of flux towers to increase in number and frequency because of very high diversity in agro-ecosystems and environment (Irmak, 2010).

2.2 Energy balance

2.2.1 Energy balance components

According to second law of thermodynamics, earth's surface energy must remain conserved. This basic physical law is exploited in devising all weather and climatic models. Net radiation (R_n), sensible heat flux (H), latent heat flux (LE), and ground heat flux (G) are the key components of energy balance at surface. (Oncley *et al.*, 2007). For an infinitesimally thin layer and in absence of horizontal advection, net radiation is the sum of latent, sensible, ground heat fluxes and soil storage term (Irmak *et al.*, 2014). Suppose fluxes are directed toward the ground then by sign convention, all the radiative fluxes are taken as negative and non-radiative fluxes as negative. Ground heat flux and storage terms are sometimes ignored in particular when we are balancing the energy balance component on daily time steps or when our experimental area have tall vegetation for example forest (Irmak *et al.*, 2014).

Tanner (1960) reported that vertical energy balance produces dependable estimates of the evapotranspiration when measurement are made close to reasonably

homogeneous surface. He also reported that heat exchange at soil surface is considerable portion of the total energy exchange even in high population mature corn crop. Oncley *et al.* (2007) performed energy balance on cotton crop under flooding water regime and he reported that of the total available energy for partitioning sensible heat flux were very small as compared to latent heat flux. Considering the diurnal pattern he also reported that closure of energy balance was least during daytime and this period show high degree of imbalance.

2.2.2 Energy balance inside crop canopy

Energy balance studies are also useful in study and analysis of various ecosystem. Ecosystem which are far from equilibrium show more water loss through evaporation as the way to maximize their entropy production and vice versa is true for near equilibrium ecosystem. Worrall *et al.* (2017) used energy balance technique to check if peat-land ecosystem of United Kingdom is in equilibrium or not. The energy balance showed that peat-land showed high value evaporation to net radiation ratio which points to the fact that this ecosystem is near to equilibrium. Global energy balance momentarily influences the evolution of the earth because changes in it affects the thermal environments on the land, atmospheric and oceanic circulations patterns, hydrological cycle, glaciers, primary productivity, and terrestrial carbon uptake. Now a days this condition is magnified massively due to global warming cause changes in the earth's energy balance so there is a need to study and understand global energy balance thoroughly. (e.g., Ramanathan *et al.*, 2001; Mercado *et al.*, 2009; Wild *et al.*, 2008). Wild *et al.* (2013) gave global perspective of the energy balance. From energy balance study of the earth satellite and ground data using CMIP5, it was estimated that surface net radiation available globally is 106 Wm^{-2} which is partitioned amongst the non-radiative surface energy fluxes. It was also observed worldwide that the simulated surface sensible heat flux (H) on an average is 20 Wm^{-2} and latent heat flux (LE) is approximately 85 Wm^{-2} .

Narrow hedge row vineyard crop yields a unique diurnal pattern of net irradiance over canopy which is characterized by morning and noon peaks (arising at the time of maximum direct solar radiation insolation on east and west sides of crop rows) with a mid-day plateau in meantime. While considering energy balance in vineyard, soil and canopy should be regarded as interdependent systems because

sensible heat generated at soil surface has a great influence on energy balance of vineyard canopy (Heilman *et al.*, 1994).

Energy balance is affected by many factors and thus different landscape and surfaces show unique energy balance pattern. Surface roughness effects the partitioning of available energy into LE and H. With increase in surface roughness, more and more part of the total available energy gets partitioned into latent heat flux, as seen when the ratio of climatological and surface resistance was less than 0.7 (DeHeer-Amissah *et al.*, 1981). Change in landscape alters energy balance of that place, for example logging down tree on a large scale (deforestation) changes energy balance by altering its albedo, surface roughness etc (Gash and Shuttleworth, 1991). Presence of lake in a region can alter energy balance of that area in a unique way by making the region infested with lake a high-energy system in comparison to other terrestrial ecosystem (Rouse *et al.*, 2005). This was because of the fact that lake receive more net radiation than uplands due to lesser amount of cloud overcast over lakes owing to stable atmospheric conditions. Again these high net radiation is stored in colossal amount by the lakes and released as massive convective heat fluxes in early winter and autumn season (Rouse *et al.*, 2005). Glacier region too show interesting unique energy balance pattern. In glacial region a larger portion of the energy flux was reported to be constituted by net shortwave radiation, while the LE values were relatively a small portion of energy flux and H of intermediate magnitude (Greuell and Smeets, 2001).

2.2.3 Energy balance through remote sensing

Now a days, there is availability of many satellite based energy balance methods ex- SEBAL, METRIC etc. SEBAL is an algorithm for surface energy balance on terrestrial surface given by Bastiaanssen in 1995. SEBAL uses surface temperature values, hemispherical surface reflectance, and Normalized Difference Vegetation Index (NDVI) as model inputs and gives energy balance as output for a variety terrestrial surfaces based on these parameters. METRIC model has its roots in SEBAL but it has relatively more advantage and accuracy because METRIC takes into account the advective effects for calibration purpose and for extrapolation of ET values over landscape (Allen *et al.*, 2007). Choi *et al.* (2009) though showed some concern over METRIC model as well as Trapezoid interpolation model because even though it showed reasonable agreement with tower flux estimates, but bias were very significant

and can't be ignored. Data from Landsat Thematic mapper can also be used to estimate surface energy balance components with appreciable accuracy as reported by Moran *et al.* (1989) according to whom it showed only difference of 12% and lower when compared with BREB system and aircraft estimates of fluxes. He also reported problem regarding this method such as atmospheric correction, crop height estimation over diverse agriculture areas and in acquisition of aerodynamic temperature as the temperature acquired radiometrically by the sensors on-board may not be equal to the aerodynamic temperature. In remote sensing technique superficial temperature of land is one of the most informative parameter which is of great help in partitioning of available energy into sensible and latent heat fluxes. Land surface temperature changes in response to net radiation contains signature of the relative magnitude of surface energy balance components (Bateni *et al.*, 2012). Latent heat flux was reported to vary considerably with air temperature under moist soil and unstressed vegetation conditions (Bateni *et al.*, 2012).

2.2.4 Energy balance Closure

Following law of conservation of energy, ideally energy balance must be closed or it must be balance and this property can be exploited to examine the quality of fluxes calculated using eddy-covariance method (Foken *et al.*, 2008). Closure of energy balance is influenced by many factors like type of coordinate system used, the footprints of individual energy balance components, and meso-scale transport (Foken *et al.*, 2008) though earlier (Foken, 1998) it was reported to have occurred due to partial canopy cover and exclusion of soil heat storage component. A full-fledged study name energy balance experiment (EBEX-2000) was devised for investigating the cause of this problem. The findings suggested that this problem is related to scale and closure is conceivable easily on the scale of landscape and it has nothing to do with measurement errors which are small or soil storage components (Foken *et al.*, 2008).

BREB method in this respect is very advantageous as it ensure closure of energy balance equation unlike eddy method because it helps in partitioning of available energy into the sensible and latent heat flux using Bowen ratio (Bowen 1926). Bowen-ratio method closes the energy balance and this leads to the resultant latent and sensible heat fluxes being related to the landscape (Foken *et al.*, 2008).

2.2.5 Urban Energy Balance

Urban areas or cities suffers more heat stress than rural areas due to lack of sufficient surface moisture availability for evaporation and low wind speeds due to more surface roughness. That is why often urban areas are also referred to as “Heat Islands” with this phenomenon reaching its peak during night (Li & Zeid, 2013).

A comparing suburban area energy balance with rural site showed higher values of net radiation, sensible heat fluxes by a magnitude of 4% and 51 % respectively, while a decrease in latent heat flux by 46% (Cleugh and Oke, 1986). Bowen ratio value were also reported to be higher for suburban areas (1.28) than the rural areas (0.46) indicating more amount of available energy is partitioned to sensible heat flux in suburban area, heating it up. The extent of urbanization has also effects on energy partitioning. Greater extent of urbanization showed higher values of Bowen ratio. It is obvious from the findings of Tejeda-Martinez and Jauregui, 2005 according to which near the less urbanized park the energy balance showed pattern were similar to that mid latitude while in the heart of downtown Mexico City the Bowen ratio values were comparable to that of desert. Peak of net radiation and heat storage near surface also showed phase lag between these two places.

2.3 Bowen ratio energy balance (BREB) method

Bowen (1926) gave this ratio on the basis of resemblance of evaporative and diffusion process of water vapour from any water surface to that of conduction or "diffusion" of specific heat energy from the water surface into the same body of air. Evaporation can be estimated by calculating this ratio from temperature and vapour pressure data and then incorporating it in the Cumming's energy balance equation (Bowen, 1926). This method of partitioning available energy into sensible (H) and latent heat (LE) flux came to be known as Bowen ratio energy balance method (BREB). Even though it was originally developed for water surface but it has been increasingly used for the other surface types as well. BREB is the most conservative of the meteorological methods for estimating latent heat flux because in this method net radiation component (R_n), puts rational limits on the magnitudes of H and LE (Perez *et al.*, 2008). Due to these reasons, partition of energy at the surface is usually obtained using the Bowen ratio-energy balance method (Kustas *et al.*, 1999) by means of the Bowen ratio as the ratio of sensible and latent heat fluxes.

At the surface, energy partitioning is a multifaceted function of interactions between development of the atmospheric boundary layer and plant physiology. Considering this fact Bowen ratio can be articulated as the function of climatic, aerodynamic and surface resistance. (Wilson *et al.*, 2002; Lockwood, 1979). Bowen ratio (B) at the surface, can be expressed as a function of a climatic factor and surface factor. Calculating surface factor as function of meteorological variable prove very helpful in determining Bowen ratio, H and LE in semi-arid conditions. (Perez *et al.*, 2008).

Climatic type has influence on energy balance. Generally, in regions with very limited soil moisture (arid and semiarid areas), during the day the gradient of water vapour pressure was found to be lower and that of the air temperature to be higher in comparison to humid regions (Miller, 1982). Land use change has also effect energy balance of land by changes the albedo, Bowen ratio, leaf area index (LAI), water availability and carbon assimilation capacity (Betts *et al.*, 1996; Pielke *et al.*, 1998). Albedo increases and the magnitude of Bowen ratio decreases when forests are cut down and transformed into agriculture land (Betts *et al.*, 1996) because of the fact that crop has comparatively higher physiological capacity of transpiration and carbon assimilation (Kelliher *et al.*, 1995; Baldocchi and Meyers, 1998).

Now a days Bowen ratio is used in many aspect of energy flux research but the first direct application of Bowen ratio concept was done by Cummings and Richardson (1927), to estimate evaporation from sea. Spittlehouse and Black (1980) used BREB method to calculate forest evapotranspiration. On comparison with eddy covariance method, a stomata diffusion resistance method and a soil water balance method, it was found that BREB method is in agreement generally within $\pm 20\%$ and frequently within $\pm 10\%$. Thus suitability of BREB method for measuring forest evapotranspiration and its reliability for continuous measurements of evapotranspiration over long periods of time was proved. Angus and Watts (1984) reported that, the Bowen energy balance method can give good ET estimates under moist conditions, but the method may not so such extent of accuracy under very dry conditions, or highly advective moist conditions. In dry conditions, the absolute error in evapotranspiration is always fairly small, because of the small value of evapotranspiration itself.

2.3.1 Modifications of BREB method

Malek *et al.* (1992) used BREB and Penman–Monteith method (PM) for continuous determination of aerodynamic and alfalfa canopy resistances. BREB method was found to be a reliable technique to study the response pattern of aerodynamic and canopy resistances response to short-term variations in weather elements such as photosynthetically active radiation (PAR), wind speed and saturated vapour deficit. These findings were also confirmed by Steduto and Hsiao (1998) who studied Maize canopies under two soil water regimes for checking validity of Bowen ratio–energy balance technique for measuring water vapour and carbon dioxide fluxes at 5-min intervals. They reported BREB technique to valid, accurate and reliable not only for measurement of fluxes over crop field but also in resolving rapid changes in fluxes brought about by canopy responses to environmental factors, especially radiation.

Oladosu *et al.* (2007) using BREB method on a humid tropical farm (Nigeria) reported that latent heat flux is approximately equal to sensible heat flux in dry days but higher in wet day conditions. Latent heat is the next essential factor after radiation in the energy balance of tropical agricultural site which is due to the prevailing humid conditions in tropics (Oladosu *et al.*, 2007). In an alpine environment even though the region above timberline has greater amount of available energy but still the locations above and below the timberline had comparable evapotranspiration (Konzelmann *et al.*, 1997).

Zhang *et al.* (2007) applied BREB for determining crop water consumption in a vineyard over season. BREB method ET estimates were found to be more accurate for vineyard in comparison with soil water balance method. In the vineyard crop, all energy balance components showed midday peaks in their diurnal cycle, with only ground heat flux showing a delay in its peak by 2–3 hours. As the crop of vine was under limited irrigation regime so the latent heat flux was controlled by available soil moisture. Shen *et al.* (2004) measured the energy balance components above the surface of an irrigated wheat and corn crop using the Bowen ratio method. It was found that, LE shows apparent relation with the development of phenology, e.g. LAI. Three typical pattern of diurnal Bowen ratio (B) which are- wheat pattern, maize pattern and a winter pattern were identified. The ‘wheat pattern’ was found to show steep morning peaks followed by a decrease with the daytime of the B, while ‘maize pattern’ showed relatively flat

course with a mean value of around 0.20–0.25 during daytime. The winter pattern is characterized by near-noon high peak with a daytime mean of more than 10 times that those for wheat or maize.

Thus BREB is clearly a very practical method. Realizing the importance of this methods a network of flux towers are erected based on Bowen ratio energy balance method under NEBFLUX project (Irmak *et al.*, 2010), to look into long-term trends and magnitudes of ET and other surface energy balance components for different agricultural and natural ecosystems.

2.3.2 Advantages of BREB method

There are many advantages offered by Bowen ratio energy balance method like robustness, portability, less affected by instrumental errors, high spatial applicability, and non-extensive data correction methods, unlike other methods (i.e., eddy covariance systems) (Irmak *et al.*, 2014). It does need estimation of any surface dynamic properties and this method can be applied for a wide range of surface from water body, forests to crop fields (Cummings and Richardson, 1927; Spittlehouse and Black, 1980; Zhang *et al.*, 2007). It is a reliable technique making it as one of the most acceptable methods which is even used to calibrate and test different empirical and physically based temperature, radiation, or combination based equations and soil water balance methods for evapotranspiration estimation (Irmak *et al.*, 2014). Though sometimes large differences among the Bowen-ratio method, eddy-correlation Method, and lysimeters in calculated ET rate values are observed over small periods (day, week, or month) , the differences tends to be small between the methods when averaged out over a year or longer particularly between BREB and lysimeter (Tomlinson, 1996). Bowen ratio energy balance method is less sensitive to instrumentation errors and flexible in respect to fetch requirements because net radiation and soil heat flux whose difference represents available energy for partitioning pose a reliable limit on turbulent fluxes, adding to the accuracy of this method (Tanner, 1960).

Gavilán and Berengena, 2007 reported that BREB method is reasonably accurate and reliable for estimating latent heat flux in advective conditions in the Guadalquivir River valley, with an overestimation of only 5.5% when compared with lysimetric estimates. Under stable atmospheric condition differences between these two methods were so meagre that there were no detected even in hourly time steps. Held *et*

al. (1990) combined BREB system with an infra-red gas analyser (IRGA) and used to estimate evapotranspiration and net CO₂ flux over crop canopies. Bowen Ratio Technique can also be used for partitioning latent heat flux between maize transpiration flux and soil surface evaporation flux components. LE arising due to maize transpiration can be determined by calculating the difference between latent heat flux of the maize field and soil surface (Zeggaf *et al.*, 2008). BREB method can estimate latent heat fluxes effectively for brief time periods which can be integrated over time for longer periods with accuracy level comparable to that of weighing lysimeters (Fritschen, 2005). On comparison of BREB method LE estimates, with lysimeters in the semi-arid region over an agriculture season, it was found that in advective environment of the southern High Plains greatest differences between these two methods occurred on hot dry and windy days (Todd *et al.*, 2000).

Bowen ratio also gives accurate, and reliable estimates of evaporative fluxes over sloping surface. Nei *et al.* (1992) study showed the absence of any detectable parallel temperature and vapour pressure gradients at a height of 1.2 m above the canopy, and Bowen ratios showed similarity along a distance of 10-40 m from top. Rosenberry *et al.* (2007) showed so much confidence in BREB method that he compared other fifteen methods like Priestley–Taylor, deBruin–Keijman, Penman method etc to the BREB method, taking BREB methods as reference. Xing *et al.* also use BREB method to validate the Penman-Monteith (PM), Priestley-Taylor (PT), and 1963 Penman equation (PE) where he found out that these other methods overestimates ET compared to BREB setup by 5 to 14%.

2.3.3 Disadvantages of BREB method

Even though there are many advantages in BREB method yet there are some reservations about its performance in advective areas. It estimated LE accurately in semi-arid advective environment accurately but it was slightly less accurate in stable atmospheric conditions. Poor fetch was considered to be the most important source of error, which resulted in local advection effects. Nevertheless, this departure from ideal fetch had only a minor effect on the BREB estimates, mainly due to small values of Bowen ratio (Gavilán and Berengena, 2007).

The theoretical limitations of the BREB can often produce extremely inaccurate magnitudes of the fluxes when the Bowen ratio approaches -1 or is -1 (Ohmura, 1982).

There is a big concern issue because under these conditions, ET estimates can become erroneous to a large extent. This condition occurs in pseudo-adiabatic atmospheric conditions (Savage *et al.*, 2009).

For removing this kind of inconsistency from BREB method using energy balance studies there is need to have set of norms for rejecting data that produce such fraudulent results. Ohmura (1982), Perez *et al.* (1999), and Savage *et al.* (2009) performed studies on Bowen ratio data rejection criteria, which depend partially on the resolution limits of relative humidity sensors and the ambient air temperature measuring instrument. Many research proposed a complete rejection of flux data corresponding to Bowen ratio ranging from -1.25 to -0.75 (Cellier and Olioso, 1993; German, 2000), which corresponds to criteria from Ohmura (1982), or a range of -1.3 to -0.7 as suggested by Unland *et al.* (1996). Generally this type of error occurs around dawn and dusk period which is a very minor portion of the daylength; therefore, the error introduced in sums of latent heat flux over a day is reasonably small (Angus and Watts, 1984).

2.4 Advection

Advection is the horizontal (parallel to land surface) divergence of sensible heat flux given it is significantly large enough in magnitude such that it produces a downward sensible heat flux near to the surface (McNaughton and Jarvis, 1983; Diaz-Espejo *et al.*, 2005).

Energy balance of the agriculture fields can be distorted to a large extent under the effects of such advections. In irrigated agricultural fields advection cause great enhancement in the process of evapotranspiration, particularly in semi-arid and arid regions (Rosenberg, 1969; Hanks *et al.*, 1971). Li and Yu (2007) reported that advection has major role in the energy exchange over extensive heterogeneous surfaces having variability in soil water regimes, weather etc. They also reported that heightened advective state was reached when values of canopy–air temperature difference become negative and the magnitude of Priestley–Taylor parameter exceed 1.5.

Spronken-Smith *et al* 2000 investigated the surface energy balance in an irrigated urban park in suburban Sacramento, CA. Strong advective effects were observed under such condition particularly in the afternoon and dusk, which may be due to differences in surface and air temperature, and humidity, between the cool, wet

park and its warmer, drier built-up surroundings. Allen *et al.* (2007) reported remote sensing based evapotranspiration models as the best tool to determine evaporative fluxes at regional scale and heterogeneous landscape effected by advection.

2.5 Fetch

The horizontal distance from the location of the sensor to the upwind edge of the studied surface is called fetch of the sensor. Layer unaffected by upwind surfaces, as a function of the distance to the edges of the surface under consideration, is called fetch-to-height ratio. (Irmak *et al.*, 2014).

Determining fetch requirement should be given more emphasis when we are using BREB method rather than eddy covariance methods because calculation of Bowen ratio requires data from sensor at two different heights (Stannard, 1997). Even though sensor data are required from two different heights, still Bowen ratio is calculated based on an assumption that the measurements are detected from the equilibrium boundary layer. This assumption makes it necessary to have sufficient fetch distance in most surface energy-based ET determination methods (Irmak *et al.*, 2014).

Heilman *et al.* (1989) in order to evaluate fetch requirement of BREB method measured Bowen ratio at different fetch-to-height ratios simultaneous over an aerodynamically even plot of Bermuda-grass which was downwind of an aerodynamically rough cotton field. On comparing flux data from multiple sensor at different fetch it was found that departure from ideal fetch (measurement within the equilibrium sub-layer) had only very meagre effects on flux estimates.

On applying Lagrangian particle trajectory model, the 100:1 fetch to height rule of thumb was found to underestimated fetch requirements for flux measurements over smooth surfaces under unstable conditions (Leclerc and Thurtell, 1990) This finding was also evidenced in Hsieh *et al.* (2000), who found fetch: height ratios of 100:1 for unstable, 250:1 for neutral, and 300:1 for stable conditions needed to condition fluxes over a surface having roughness of 0.04 m. Monteith and Unsworth (1990) recommended a fetch of 50:1 for micrometeorological measurement of sensible and latent heat flux. The theoretical considerations of boundary layer development that can be used to estimate minimum fetch requirements as a function of surface roughness was given by Brutsaert (1982). On the assumption that lower 10% of an internal boundary layer downwind of a surface discontinuity has reached full adjustment to a new

equilibrium with the surface (Petersen, 1969; Brutsaert, 1982), the Brutsaert's equation of minimum required fetch for complete boundary development (in near neutral condition) can be expressed as function of maximum height of the sensor from the ground, zero plane displacement and momentum roughness height of the surface. With increase in instability the exponent of the equation is decreased (Brutsaert, 1982). This equation showed that surface roughness and fetch requirement are inversely proportional. It was found that 100:1 fetch rule is valid for a comparatively wide range of vegetation and equipment heights. According to the equation, the 100:1 rule represents most closely 0.12-m tall vegetation but in case of open water due to lack of roughness the equation becomes senseless and fetch requirements become large for open water (Petersen, 1969).

Allen (2006) study on effect of fetch on vapour pressure and temperature measurements showed that the 100:1 fetch thumb rule apply well to unstable atmospheric conditions (characterized by positive Bowen ratio values) for measurement of temperature and humidity at weather stations but it might underestimate the fetch requirement for neutral and stable conditions. For better accuracy and reliability on estimated fluxes, air-temperature and vapour-pressure differences should be measured closer to the surface. Fetch requirement increases with rise in wind speed and decrease in the ability of the surface to evapo-transpire (Fritschen, 2005).

3. MATERIAL AND METHODS

In order to attain the research objectives, field experiment on maize and wheat crop were conducted under irrigated condition during *kharif* (2017) and *rabi* (2017-18) season, respectively. The specifics of the material and methods adopted during the course of present study is

given in this chapter.

3.1 Field Experiments

3.1.1 Details of the experimental site

This study was conducted in the experimental farm (Main Block 4C) of ICAR-Indian Agriculture Research Institute, New Delhi located at 28°37'N latitude and 77°09' E longitude, and at an altitude of 228.16m above mean sea level.

3.1.2 Climate

The climate at the location of experimental site in ICAR-IARI is subtropical to semi-arid characterized by hot and dry summer and cold winter season. It also experiences monsoon rain in the summer months during end of June to September. This region belong to 'Trans-Gangetic plains'. Diurnal changes in temperature are maximum during summer months of May and June with their magnitude ranging from 40°C to 46 °C. Daily maximum temperature of highest magnitude (46.8°C) was recorded on 29th May, 1998. Minimum temperature ranging from 3.4 °C to 5.5 °C is experienced in the month of January during winter. Lowest daily minimum temperature of magnitude -1.4 was recorded on 9th January, 2006. Annual mean rainfall is 710 mm with July- August as the wettest months during the whole year. Major amount of the annual rainfall (about 80%) is received from south-west monsoon during the period of July to September. The rest amount of rainfall is received from "Western Disturbances" during winter season (December to February). Mean values of meteorological parameters (except rainfall) recorded at the IARI agro-meteorological observatory during *kharif* season 2017 and *rabi* season 2017-18 are presented in table 3.1.

Table 3.1: Weather data of *kharif* season 2017 and *rabi* season 2017-18 recorded at Agromet observatory of ICAR-IARI, New Delhi.

SMW	Date	Temperature		Rainfall	WS	RH (%)		BSS	EP
		Max.	Min.	(mm)	(kmph)	Max.	Min.	(hrs)	(mm)
Kharif season 2017									
27	02-08 Jul	33.9	25.8	6.6	5.2	87.7	63.9	2.9	4.8
28	09-15 Jul	35.4	26.5	1.1	5.9	62.7	73.6	6.4	5.1
29	16-22 Jul	34.6	26.6	3.1	5.3	86.4	67.0	4.9	4.6
30	23-29 Jul	33.2	25.9	6.9	6.3	89.3	78.1	5.4	4.0
31	30-05 Aug	32.4	26.0	1.2	7.2	87.9	73.0	2.0	3.9
32	6-12 Aug	34.1	26.3	11.9	5.3	89.4	72.9	2.4	4.3
33	13-19 Aug	35.2	26.4	3.9	7.9	89.9	69.3	6.2	5.2
34	20-26 Aug	33.2	25.6	9.4	3.5	92.7	80.4	4.1	5.0
35	27-02 Sep	32.6	24.9	9.7	5.3	93.1	79.3	4.1	4.5
36	03-09 Sep	33.3	24.2	0.6	4.9	92.6	69.3	7.3	4.7
37	10-16 Sep	35.8	24.8	0.0	3.5	93.1	54.6	7.4	4.8
38	17-23 Sep	33.5	23.4	19.8	4.4	76.7	65.3	4.0	4.2
39	24-30 Sep	32.7	21.9	0.5	4.3	93.3	52.0	7.4	3.9
40	01-07 Oct	35.3	19.6	0.0	3.6	88.9	40.7	9.2	5.4
41	08-14 Oct	34.3	19.3	0.0	2.0	93.6	43.1	6.8	3.7
42	15-21 Oct	34.9	16.4	0.0	2.1	93.1	41.1	6.9	3.8
43	22-28 Oct	32.9	14.8	0.0	2.2	91.7	42.3	4.0	3.2
44	29-04 Oct	29.8	15.1	0.0	1.6	94.0	55.1	1.2	2.8

SMW	Date	Temperature		Rainfall (mm)	WS (kmph)	RH (%)		BSS (hrs)	EP (mm)
		Max.	Min.			Max.	Min.		
Rabi season 2017-18									
45	5-11 Nov	28.6	12.4	0.0	1.3	95.1	50.3	0.0	0.2
46	12-18 Nov	26.4	12.3	0.0	2.5	92.1	54.1	0.0	0.2
47	19-25 Nov	24.5	7.4	0.0	4.0	73.3	45.3	0.0	5.8
48	26-02 Dec	26.0	6.1	0.0	2.0	88.7	39.7	0.0	6.5
49	03-09 Dec	24.1	8.9	0.0	2.7	72.2	45.3	0.0	3.3
50	10-16 Dec	20.6	7.1	0.0	3.8	96.6	63.3	0.0	3.2
51	17-23 Dec	23.4	8.0	0.0	4.6	85.3	51.0	0.0	4.9
52	24-31 Dec	23.0	4.1	0.0	1.7	91.9	49.1	0.0	5.0
1	01-07 Jan	18.3	4.0	0.0	2.1	94.6	56.1	0.0	1.2
2	08-14 Jan	21.4	3.0	0.0	4.0	91.3	44.0	0.0	5.3
3	15-21 Jan	22.8	3.4	0.0	3.3	92.4	37.7	0.0	6.5
4	22-28 Jan	19.0	5.5	0.9	3.7	94.4	65.1	0.9	3.4
5	29-04 Feb	23.8	6.7	0.0	4.0	76.5	36.0	0.0	15.2
6	05-11 Feb	22.5	4.6	0.0	3.3	78.4	31.9	0.0	5.8
7	12-18 Feb	23.0	9.2	0.0	5.9	77.3	51.7	0.0	5.9
8	19-25 Feb	28.4	10.5	0.0	2.5	88.0	40.3	0.0	6.3
9	26-04 Mar	29.0	12.8	0.0	4.4	88.9	104.9	0.0	7.2
10	05-11 Mar	29.4	11.6	0.0	5.2	91.1	34.9	0.0	8.5
11	12-18 Mar	31.9	12.8	0.0	4.4	84.7	30.0	0.0	7.7
12	19-25 Mar	31.5	14.9	0.0	5.1	80.4	29.3	0.0	8.6
13	26-01 Apr	35.2	15.0	0.0	5.7	71.3	24.7	0.0	9.4
14	02-08 Apr	30.17	16.97	45.8	4.66	90.00	50.29	6.50	4.54
15	09-25 Apr	31.90	17.71	6.0	4.99	77.29	45.86	7.23	5.04

3.1.3 Soil

The soil of the study site have sandy loam texture in upper 30 cm layer from the surface. The soil nutrient status was found to be poor for available nitrogen and medium in organic carbon content and phosphorous availability. Representatives soil sample were also collected from this site and analysis was carried out to determine various physio-chemical properties of the soil which are given below.

Table 3.2: Soil physio-chemical properties of the experimental site.

S. No.	Particulars	Content
Physical characteristics		
A)	Sand (%)	62.5
	Silt (%)	18.2
	Clay (%)	19.30
	Textural class	Sandy clay loam
	Bulk density(0-15 cm soil) (g/cc)	1.52
Chemical characteristics		
B)	Organic carbon (%) (Walkley and Black,1934)	0.53
	Available nitrogen (N kg ha-1) (Subbiah and Asija, 1956)	170.5
	Available phosphorus (P kg ha-1) (Olsen <i>et al.</i> , 1954)	18.6
	Available potassium (K kg ha-1) (Flame photometer method, Hanway and Heidel, 1952)	275.0
	pH (1:2.5 soil: water) (Cyber scam 500 pH meter)	8.0

3.2 Crop

A field of 1620 m² was used for the experiment. The cultivar PMH-1 was selected for the study which is a *kharif* late maturing hybrid variety of maize. For *rabi* season 2017-18 HD 2967 was selected which is a double dwarf variety of wheat with

an average yield 44.4 -50.4 qt/ha. It is also resistant to yellow and brown rusts and takes about 157 days to mature.

3.3 Date of Sowing

The maize crop was sown on 19th July, 2017 during first year of experiment and wheat on 24th November, 2017.

3.4 Experimental Layout

The field consists of homogeneous plot of maize in *kharif* season 2017 and wheat crop in *rabi* season 2017-18 as in whole field same variety was grown under uniform management practices. The details of the experimental setup is given in table 3.3.

Table 3.3 Experimental set-up details

Crop	Maize (PMH-1)
Date of sowing	19 th July, 2017
Spacing	60 cm×20cm
Design	Homogeneous plot
Plot area	1620m ²
Management	Standard management practices
Crop	Wheat (HD 2967)
Date of sowing	24 st November, 2017
Spacing	22.5 cm (row to row)
Design	Homogeneous plot
Plot size	7 m x 7 m
Plot area	1620m ²
Management	Standard management practices

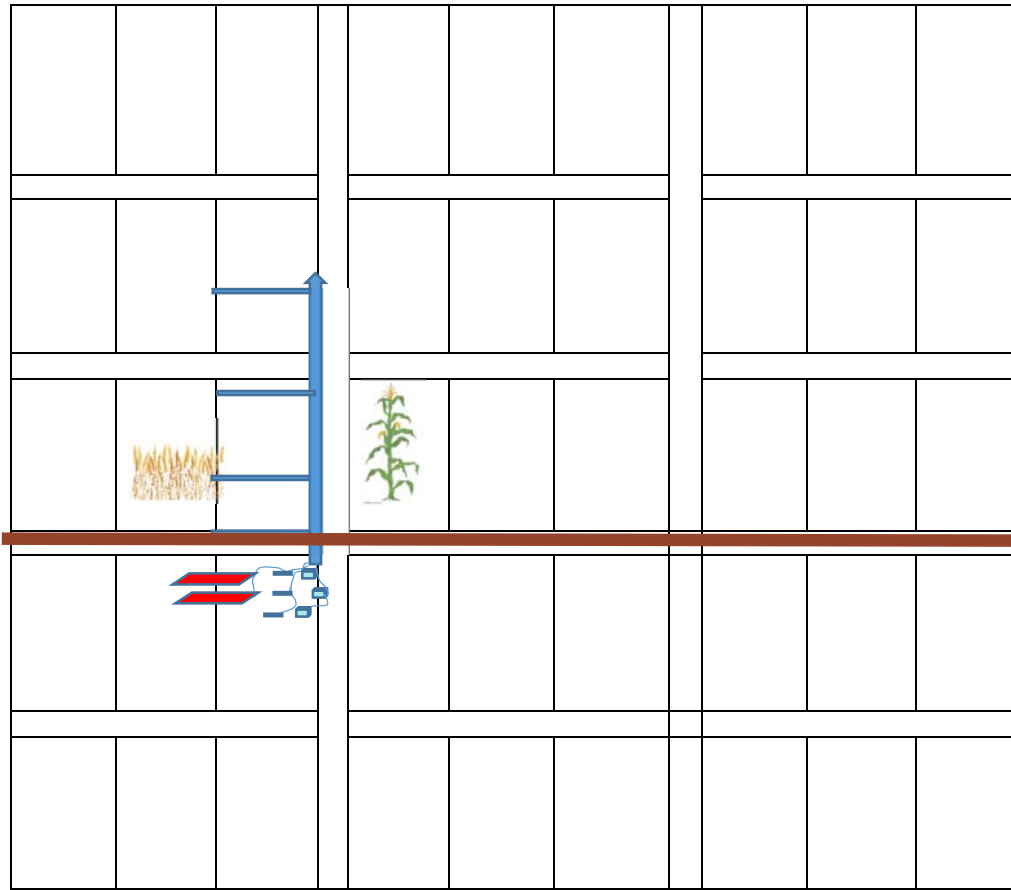


Fig. 3.1 Layout of experiment in a homogeneous field of maize (*kharif*) and wheat (*rabi*) crop under irrigated condition and standard management practices. The arrow in the layout represents micrometeorological tower position in the field with various sensors above and below the ground.

3.5 Agronomic practices

Standard agronomic management practices recommended for the experimental region were followed for both crops. Maize crop was given four irrigation (seedling, knee high, silking and dough stage) and fertilizer dose of N: P₂O₅: K₂O@150:75:75. Wheat crop was given five irrigations (CRI, tillering, jointing, flowering and grain filling stage) and a recommended fertilizer dose of N: P₂O₅: K₂O@ 120:60:60.

3.6 Observations schedule

The observations were recorded and measured for different parameters like global solar radiation, weather parameters, plant phenology and morphology, crop micrometeorology and soil moisture. The micrometeorological parameters are taken at



(a)



(b)



(c)

Plate 1. (a) Micrometeorological tower inside crop field with (b) data logger, from which (c) downloading of data to personal computer is done



Plate 2. Micrometeorological tower with temperature, humidity, and wind speed sensor at various height (0.5m, 1m, 2 m)

hourly intervals which include soil heat flux, radiation, wind speed and relative humidity.

3.6.1 Weather parameters

Different weather data like minimum and maximum temperatures, morning and evening relative humidity (RH), wind speed, bright sunshine hours (BSS), evaporation and rainfall were collected from the agro-meteorological observatory of the Division of Agricultural Physics, IARI, New Delhi.

3.6.2 Crop parameters

3.6.2.1 Crop Phenology

Crop phenology was monitored twice in a week, by observing the plants in the field and the following phenological events were observed:

Maize:

- a) Crop emergence- when maize seedling has emerged with four leaves on it.
- b) Knee high stage- when crop reaches to a height of 60-65cm
- c) Tasseling stage- when male inflorescence of maize emergence at top.
- d) Silking stage- when stigma of the female flower inflorescence emerge.
- e) Dough stage- hardening of the grain.
- f) Grain maturity stage- attainment of physiological maturity by grain.

Wheat:

- a) 50% germination- when 50% seedlings emerged.
- b) Crown root initiation (CRI) - 21 days after sowing, development of transition zone between root and shoot.
- c) Tillering stage- when 3-7 tillers came from main shoot.
- d) Jointing/booting stage – when flower buds emerge out.
- e) Flowering stage- when anthers visible outside the panicle of 50% plants.
- f) Milking stage- when a white liquid comes out after pressing the seed coat with fingers.
- g) Dough stage-when milky fluid in wheat ears turns harden.
- h) Physiological maturity- when all leaves senesced.

3.6.2 Plant bio-physical parameters

Different biophysical parameters like leaf area index (LAI), biomass were recorded at weekly/10 days intervals. Plant height was also measured at regular intervals.

3.6.2.1 Biomass Accumulation

Plant biomass was calculated at regular intervals during crop life cycle of maize and wheat on the basis of weekly measurement. Measurements were taken by selecting four plants randomly from each plot and cutting the stem at ground level. Plants were then oven dried at $60^{\circ}\pm 5^{\circ}$ C for 48 hours or more and weighted by using digital balance.

3.6.2.2 Leaf Area Index (LAI)

LAI were measured weekly by using LAI- 2000 Plant Canopy Analyzer (LI-COR, USA). It is non-destructive method of estimation of LAI indirectly from measurements of radiation above and beneath the plant canopy. Its optical system have five detectors which measures the blue light interception (below 490 nm) at 5 zenith angles ($0-13^{\circ}$, $16-28^{\circ}$, $32-43^{\circ}$, $47-58^{\circ}$, $61-74^{\circ}$) simultaneously. The instrument was set to take one above and four beneath plant canopy measurements to estimate the LAI. Three LAI readings were measured in each plot and then averaged them for each plot.

3.6.2.3 Plant height

Plant height was measured from the ground to the top portion of the spikelet (do not include the awns) with the help of meter scale at regular intervals. At least three spike-bearing culms were measured per plot.

3.6.2.4 Crop Yield and Harvest Index

An area of 1 m^2 was harvested manually from each plot after maturity of wheat. These samples were weighed to get final above ground biomass (g m^{-2}). Finally, plant samples were thrashed and average grain yield and straw yield in g m^{-2} was calculated and converted to kg ha^{-1} . Harvest index (HI) was also calculated by using following formula:

$$\text{HI (\%)} = (\text{grain yield/ Final above ground biomass}) \times 100$$



Plate 3. Measurement of Leaf Area Index using Canopy analyzer (LI-2000) inside maize crop at tasseling stage during *kharif*, 2017



Plate 4. Measurement of height (at germination) in wheat (*rabi*, 2017-18) using meter scale



Plate 5. Measurement of PAR using line quantum sensor during *rabi*, 2017-18



Plate 6. Measurement of height in wheat crop at flowering stage during *rabi*, 2017- 18

3.6.2.5 Test weight/ thousand grains weight

First, thousand seeds/grains were counted for each plot by seed counter in the biophysical laboratory. After, then these grains were weighed separately for each plot on electrical digital balance and finally, the reading were noted as the test weight (grams).

3.6.3 Crop Micrometeorological Parameters

Micrometeorological tower used in this study had wind speed, relative humidity, and temperature sensor at height of 0.5, 1, 2, 4 and 8 meters. Two soil heat flux at depth of 5 and 15 cm and three soil moisture sensor at 5, 15 and 25 cm deep from the soil surface were also installed

Table 3.4 Specification of sensors in micrometeorological tower which was used for the experimental site.

S.No	Sensors	Model	Manufacturer	Specifications
1.	Data Logger	DL2e	DeltaT Devices Ltd., UK	45 Channel Data Logger. 30 Channel Analogue and 15 counters.
2	Air Temp and RH	RHt2nl	DeltaT Devices Ltd., UK	RH : Range 0-100% Accuracy +/- 2 % Temp : -50 - 150 deg C Accuracy : 0.1 degree Centigrade
3	Wind speed/Anemometer	AN1	DeltaT Devices Ltd., UK	Anemometer, with reed switch type, 3 cup weather resistant rotor Range : 0.2 to 75 m/s Error : ± 0.1 m/s
4	Wind Direction	WD1	DeltaT Devices Ltd., UK	Wind Direction Sensor : Range : 0-358 deg Resolution : 0.3 deg Accuracy : ± 2 deg
5	Quantum Sensor	QS5	DeltaT Devices Ltd., UK	Silicon Photodiode sensor, cosine corrected

				Spectral Range 400 to 700 nm Field of view: 180 ° Accuracy $\pm$ 5%
6	Soil-Moisture Sensor	SM150	DeltaT Devices Ltd., UK	Volumetric soil water content measurement based on FDR. For direct insertion in the soil. Range: 0-100% Accuracy : $\pm$ 3%
7	Soil Temp Probe	ST1	DeltaT Devices Ltd., UK	Stainless steel body, water resistant, suitable for burial for soil temperature measurement Range : -50 to 150 °C Accuracy : $\pm$0.2 °C
8	NET Radiometer	NR2	DeltaT Devices Ltd., UK	Sensor: Net Radiometer based on differential thermopile Spectral response: 0.25 – 60 μm Response time: 18 seconds (nominal) Range: 0.5 to +1 kW/m²
9.	Soil Heat Flux	HFP	HUKSEFLUX, NETHERLANDS	Differential thermopile sensor in water resistant casing Temperature range: -30 to +70 C Range : +2000 to -2000 Wm² Expected typical accuracy: 3%

Complete set of sensors are installed on 10 meter tower. Data Logger is battery operated 12V 7 Ah x 2 batteries with solar power (30W) charging system.

3.6.3.1 Relative humidity within and above Crop Canopy

Air temperature were measured within plant canopy and above the canopy at hourly scales during whole period of experiment. This was accomplished using multiple relative humidity and temperature sensors installed in the micro-meteorological tower.

3.6.3.2 Net radiation

Net radiation was measured at hourly time scales by the net radiometer installed in the tower.

3.6.3.3 Wind speed

Wind speed were measured at various height over the crop round the clock. The different height was 0.5, 1, 2, 4, and 8 meters. The data so obtained from various level across different times were used to construct the wind profile for various crop at various stages.

3.6.3.4 Air Temperature within and above Crop Canopy

Air temperature were measured within plant canopy and above the canopy at hourly scales during whole period of experiment. This was accomplished using multiple relative humidity and temperature sensors installed in the micro-meteorological tower

3.6.3.5 Soil moisture

Volumetric soil moisture was recorded by micrometeorological tower on an hourly basis at different depth of 5, 15 and 25 cm. These were averaged for a day to see the seasonal trend of soil moisture for both maize and wheat crop.

Micrometeorological tower has wind, relative humidity, and temperature sensor at height of 0.5, 1, 2, 4 and 8 meters. Two soil heat flux at depth of 5 and 15 cm and three soil moisture sensor at 5, 15 and 25 cm deep from the soil surface were also installed.

3.6.3.7 Radiation Use Efficiency

The daily values of incident PAR was recorded by quantum sensor fitted in micrometeorological tower. After then, daily intercepted PAR (IPAR) was calculated by multiplying daily incident PAR with corresponding daily fIPAR and integrated over the entire growth period.

Finally, radiation use efficiency (RUE) was calculated for grain and biomass separately, by using following formula:

$$\text{RUE}_b (\text{g/ MJ}) = \text{Biomass} / \text{TIPAR}$$

$$\text{RUE}_y (\text{g/ MJ}) = \text{Grain yield} / \text{TIPAR}$$

Where, TIPAR stands for Total intercepted PAR.

3.7 Bowen Ratio Energy Balance Methodology

The earth receives its energy from the sun and it acts as driving force to all the life as well as atmospheric processes. Not only the amount of energy is important but also its partitioning in various component fluxes. In particular when we talk about vegetation and crop then this partitioning becomes very important. So in order to study energy balance Bowen ratio technique was used to partition net radiation into component fluxes.

There are four types of energy fluxes at an ideal surface: the net radiation, the sensible heat flux, the latent heat flux. The sensible heat flux arises as a result of the difference in temperature of the surface and air above. The latent heat or water vapour flux is the result of evapotranspiration mainly over vegetative surfaces. The ground heat flux is due to conduction by soil.

Energy budget method estimates fluxes and evaporation by budgeting gains and losses over the surface. The energy balance equation is given as:

$$\text{Rn} = \text{H} + \text{LE} + \text{G} + \text{S} + \text{P}$$

Where, H = sensible heat flux

LE = latent heat flux

G = ground heat flux

S = storage term for plant canopy

P = energy utilized in photosynthesis

The S and P components are negligible in magnitude as compared to other fluxes so it is ignored. So the final equation used is-

$$\text{Rn} = \text{H} + \text{LE} + \text{G}$$

The R_n (net radiometer) and G (soil heat flux plate) were determined using micrometeorological tower. The available energy over the surface i.e. the difference between net radiation and soil heat flux is then partitioned into turbulent heat fluxes using the Bowen ratio. Bowen ratio is calculated using formula given by Bowen in 1926.

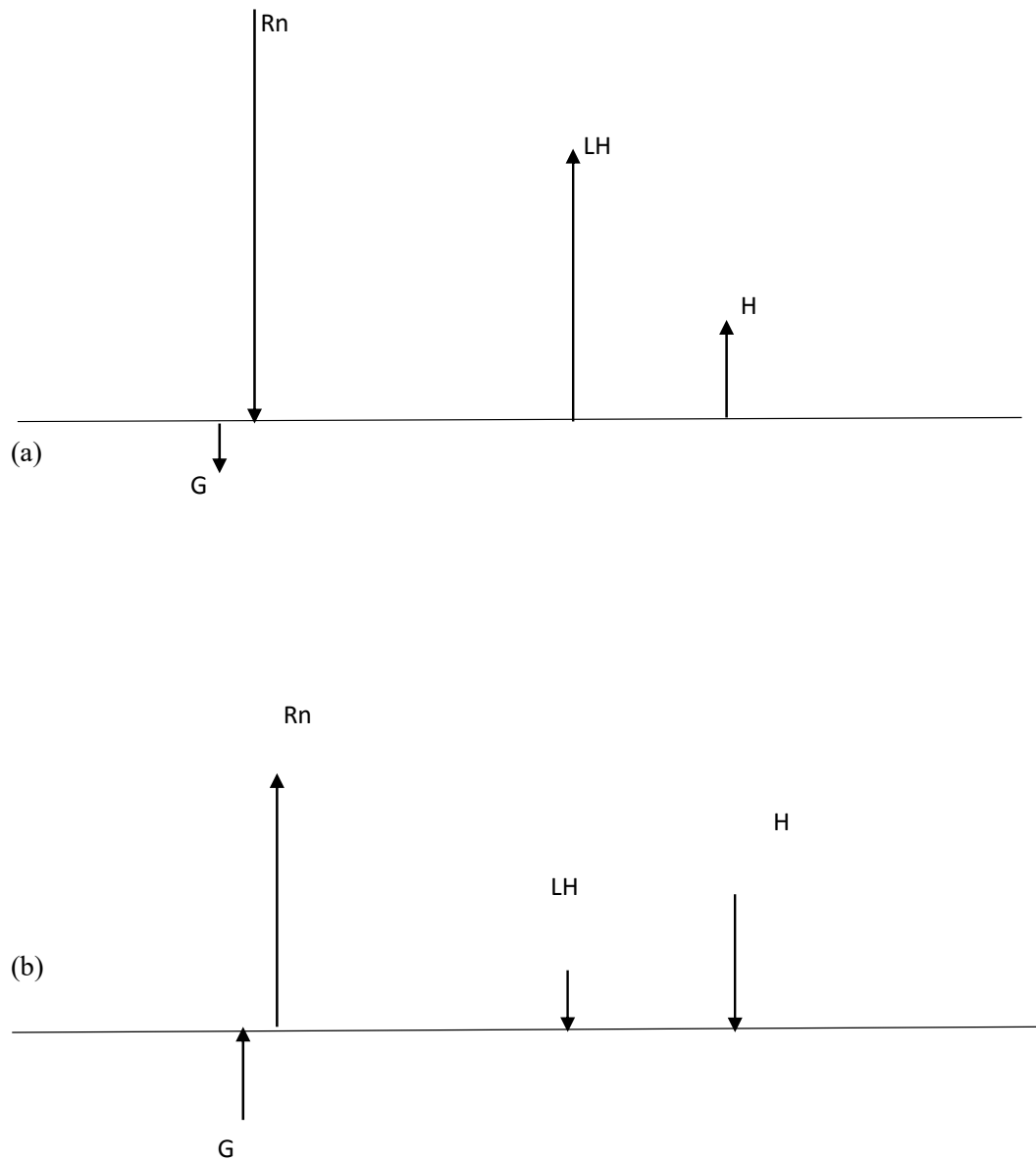


Fig 3.2 Typical representation of sign of surface energy balance components during (a) day time and (b) night

The sign convention used here is that all the radiative fluxes directed toward the surface are positive while the non-radiative fluxes directed away from the surface are positive and vice versa. Thus according to this sign convention all the terms of the surface energy balance components are generally positive during day and negative during evening and night.

On the shortest time scale, the Bowen ratio is calculated as the ratio of vertical air temperature to water vapor pressure gradients. Thus, the equations for sensible and latent heat fluxes can be expressed, following the gradient transport theory, analogous to Fick's law of molecular diffusion, providing a powerful indicator of an ecosystem's energy flux contribution to the regional climate. The formula used for Bowen ratio is given as:

$$B = \gamma (\Delta T / \Delta e)$$

Where, B = Bowen ratio

γ = psychrometric constant (k Pa °C⁻¹)

ΔT = temperature gradient (°C m⁻¹)

Δe = vapour pressure gradient (k Pa m⁻¹)

$\gamma = 0.065701 \text{ k Pa}^\circ\text{C}^{-1}$ (for my experimental site)

The Bowen ratio is also defined as the ratio of sensible and latent heat fluxes *i.e.*

$$B = (H / LE)$$

Thus once the Bowen ratio was calculated using temperature and vapour pressure gradients it was then applied to partition the net available energy into components fluxes by using this ratio in energy balance equation. Thus the equation utilized to calculate component fluxes are-

$$H = (R_n - G) / (1 + B^{-1})$$

$$LE = (R_n - G) / (1 + B)$$

Where (R_n – G) term denotes the net available energy for partitioning. Then the latent heat fluxes are converted from Wm⁻² to MJ m⁻² which is then multiplied by factor of 0.048 to convert it into mm of water. Thus the ratio of flux components for example G/R_n, H/R_n, LE/R_n can be determined as well as crop evapotranspiration (ET_c). As the

sensor were placed at multiple heights on those sensor combinations were selected at different stages whose equilibrium layer coincides with the layer over crop where transfer of latent heat fluxes are taking place and represents crop. Thus when the crop height increases, higher level sensor combinations were used so that it is representative of energy balance taking place just over the crop surface. Hence sensor combinations used are as follows-

Table 3.5 Sensor height combinations used for maize crop which grows up to a maximum height of approximately 2m and dwarf wheat with average maximum height of 0.9 – 1.0 m.

Stages	Sensor height combination used
Maize	
Germination	0.5 to 1 m
4-leaf stage	0.5 to 1 m
6-leaf stage	0.5 to 1 m
Knee high stage	2 to 4 m
Tasseling stage	2 to 4 m
Silking stage	2 to 4 m
Dough stage	2 to 4 m
Wheat	
Germination	0.5 to 1 m
CRI stage	0.5 to 1 m
Tillering stage	1 to 2 m
Booting stage	1 to 2 m
Flowering stage	1 to 2 m
Grain filling stage	1 to 2 m
Dough stage	1 to 2 m
Physiological maturity	1 to 2 m

3.8 Reference evapotranspiration

The reference evapotranspiration was calculated using FAO56 formula

$$ET_0 = \frac{0.408 \Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Where ET₀ expressed in (mm day⁻¹);

R_n net radiation at crop surface (MJ m⁻² day⁻¹)

G soil heat flux density (MJ m⁻² day⁻¹)

T air temperature at 2 m height (°C)

u₂ wind speed at 2m height (m s⁻¹)

e_s saturation vapour pressure (k Pa)

e_a actual vapour pressure (k Pa)

Δ the slope of the vapour pressure curve (k Pa °C⁻¹) and

γ is the psychrometric constant in (k Pa °C⁻¹).

The components of formula are calculated using the formula given in FAO56 paper. The reference evapotranspiration was calculated on a daily basis for the both maize and wheat crop which was then averaged for different stages of development (initial, development, mid and final stages.

3.9 Crop coefficient

It was then compared with the estimated ET_c obtained from BREB technique to calculate crop coefficient.

$$K_c = (ET_c / ET_0)$$

Where K_c= crop coefficient

ET_c = crop evapotranspiration

ET₀ = reference evapotranspiration

Table 3.6 Duration of different stages of maize and wheat crop under irrigated semi-arid, subtropical conditions.

Stages	Maize (Days)	Wheat (Days)
Initial stage	0-20	0-40
Development stage	20-45	40-70
Mid stage	45-85	70-120
End stage	85-105	120-140

3.10 Statistical Analysis

Finally, data sets were processed for analysis of variance as applicable to split plot design, to test differences among the various treatments and their interactions using Statistical Analysis System (SAS).

4. RESULT

4.1. Weather conditions during the growth period of chick pea

Maize crop was grown during *kharif* season (July-October) of 2017 and wheat was grown during *rabi* season (November – April) of 2017-18. Daily weather data during the growing season, were collected from the ICAR-IARI agro-meteorological observatory. Weekly mean values of weather parameters were calculated and analyzed according to standard meteorological weeks (SMW).

4.1.1. Weekly mean maximum and minimum temperatures

During *kharif* season of 2017, weekly mean maximum temperature ranged between 29.0°C and 35.4°C (Fig. 4.1). High temperature (35.4°C) was recorded during 28th SMW. A sudden increase in weekly mean maximum temperature was observed in 31st SMW (32.4°C), 35th SMW (32.0) and in 38th SMW (32.7°C). The lowest mean maximum temperature was observed in 43rd SMW (29.0°C). Initially, at the time of sowing mean maximum temperature was also higher in 28th SMW (35.4°C) during *kharif* season (2017).

Weekly mean minimum temperature during *kharif* season 2017 (Fig. 4.1) followed the different trend and ranged 10.7°C (43rd SMW) and 26.6°C (29th SMW). It was observed that weekly mean maximum temperature was increased in 31st SMW (32.4°C), 35th SMW (32.0) and 38th SMW (29.0°C) during the crop growth.

During *rabi* season of 2018, weekly mean maximum temperature ranged between 18.3°C and 35.7°C (Fig. 4.3). High temperature (35.7°C) was recorded during 14th SMW. A sudden increase in weekly mean maximum temperature was observed in 6th SMW (22.5°C) and in 8th SMW (26.8°C). The lowest mean maximum temperature was observed in 4th SMW (19.0°C). Initially, at the time of sowing mean maximum temperature was also higher in 46th SMW (26.4°C) during *rabi* season (2017).

4.1.2. Weekly cumulative rainfall

During the maize growth period, a total rainfall of 76.2 mm was received (Fig. 4.1). A maximum rainfall of 20.3 mm was recorded in 38th SMW and many SMW were rainfall deficit. Moderate rainfall was received in 32nd (11.9 mm), 35th (9.9mm) SMW.

Rainfall was also occurred in 29th (3.1 mm), 30th (6.9 mm) SMW, 34th (9.7mm) and 41st (5.1mm).

In *rabi* season of 2017-18, a total rainfall received was 3.37 mm (Fig. 4.3). Maximum rainfall (1.4 mm) was received during 15th SMW.

4.1.3. Weekly mean pan evaporation

During the growing season initially the evaporation rate 5.1 mm in the 28th SMW and decreases up to 3.9 mm in the 31st SMW and then increases to 2.10 mm in 33rd SMW, after this the weakly pan evaporation follows an approximate constant trend and attains the highest value of 5.2 mm during the 32nd SMW. Total pan evaporation was observed 77.1 mm during the entire growing season (Fig. 4.1).

During *rabi* season 2017-18, total pan evaporation was 75.30 mm in entire crop growing stages (Fig. 4.3). Highest pan observation 6.14 mm observed in 14th SMW and lowest was 1.44 mm in 1st SMW. Monthly values of Epan is given in table 4.1.

Table 4.1: Monthly mean pan evaporation

<i>Kharif 2017</i>		<i>Rabi 2017-18</i>	
Month	Epan (mm day ⁻¹)	Month	Epan (mm day ⁻¹)
June	5.9	November	2.3
July	4.5	December	2.3
August	4.7	January	2.4
September	4.4	February	3.5
October	3.9	March	4.2

4.1.4. Weekly mean bright sunshine hours

Bright sunshine hours data were recorded and it was observed that during *kharif* season of 2017-18 (Fig. 4.2), weekly mean bright sunshine hours ranged between 2.0 hours (31st SMW) to 9.1 hours (40th SMW). Up to 41st SMW, the trend is irregular, however, an increasing trend was observed from 41st SMW to the harvest of the crop. The major drops in bright sunshine hours were recorded in 31st (2.0 hours) and 35th (4.0 hours), 38th (4.0 hours) and 41st (6.8 hours) SMW. Two prominent peaks were observed in 33rd SMW (6.2 hours) and 36th SMW (8.4 hours).

During *rabi* season 2017-18, weekly mean bright sunshine hours ranged between 0.2 hours (46th SMW) to 15.242 hours (5th SMW). Up to 4th SMW, the trend is irregular, however, an increasing trend was observed from 4th SMW to 5th SMW and sudden decreasing trend from 5th to 6th SMW, after this week it followed an increasing trend till the harvest period of the crop (Fig. 4.4).

4.1.5. Weekly mean morning and evening relative humidity (RH)

Weekly mean morning relative humidity (RH) showed high variability during the growing season which ranges from 79.0% to 93.3%, a sudden drop was observed after 38th SMW. Initially, it was around 83.6%, but thereafter certain up and down it reached the peak of 93.3% in 36th SMW and thereafter, it decreased till 38th SMW with a peak at 39th SMW (Fig. 4.2). Weekly mean evening RH ranged between 34.2% (44th SMW) and 80.7% (35th SMW) during the growing season. There were peaks on 30th, 35th, 38th, 41th SMW and the continuous increasing trend was noticed from 28th to 30th SMW. After 41st SMW RH decreases up to 32.2% in 44th SMW, with some peaks in between.

Weekly mean morning relative humidity (RH) varied highly, during the *rabi* season (2017-18) it ranges from 65.7% to 94.5% (Fig. 4.4). Highest was recorded in 4th SMW.

4.1.6. Weekly mean wind speed

Weekly mean wind speed during *kharif* season (2017-18) varied between 1.9 to 7.9 km h⁻¹ (Fig. 4.2). The highest wind speed of 7.9 km h⁻¹ was recorded in 33rd SMW and the lowest (1.9 km h⁻¹) in 43th SMW. Three low weekly mean wind speeds (3.2, 3.4 and 3.5 km h⁻¹) were recorded in 34th, 37th and 40th SMWs respectively.

In *rabi* season (2017-18), it varied between 1.7 to 7.0 km h⁻¹ (Fig. 4.4). The highest wind speed of 7.0 km h⁻¹ was recorded in 50th SMW and the lowest (1.9 km h⁻¹) in 52nd SMW.

4.2 Crop biophysical parameters

4.2.1. Crop phenology

Phenology of the maize crop grown is presented in Table 4.2. During *kharif* 2017 on 19th July, sowing of maize was done. Cultivar used was PMH-1 which emerged in 9 - 10 DAS. The crop reached knee high stage at 38DAS and matured at 102 DAS.

The wheat crop was grown during *rabi* 2017-18 (Table 4.3). The cultivar HD-2967 sown on 24th November, 2017 germinated in 6-7 days after sowing (DAS). CRI stage appeared in 23 DAS 14 and finally harvesting was done at 140 DAS.

Table 4.2: Variation in phenology (DAS) of maize crop during *kharif* 2017.

Phenological stages	DAS
Crop sowing	19 th July
Crop emergence (four leaf stage)	10
Knee high stage	38
Taselling (50%)	50
Silking (50%)	55
Dough	86
Physiological Maturity	102

Table 4.3: Variation in phenology (DAS) of the wheat crop during *rabi* 2017-18.

Phenological stages	DAS
Crop sowing	24 th Nov 2017
Germination	7
CRI	23
Tillering	45
Booting	88
Flowering	98
Grain filling	106
Milking	117
Dough	124
Maturity	130
Harvesting	140

4.2.2. Leaf Area Index (LAI)

Leaf area index (LAI) of maize crop was varied among all observations (Table 4.4). Initial stages LAI increased during vegetative phase, then reached a peak around 80 DAS and decreased thereafter due to senescence of the crop towards maturity. Highest LAI was recorded is 4.50 at 80 DAS with a CV varied from 5.74% to 16.35 %

and CI varied from 0.14 to 0.25. Subsequently, it decreased with crop maturity (Fig. 4.5).

In *rabi* season, Leaf area index (LAI) of the wheat crop showed variation (Table 4.5). LAI was showed increasing trend initially and reached highest (5.58) in 90 DAS. After that LAI decreased with advancement towards crop maturity stage (Fig 4.6).

Table 4.4: Variation of LAI in maize crop at different growth stages under irrigated condition during *kharif* season 2017.

Observations	Days after sowing (DAS)					
	30	50	60	80	90	108
R1	1.32	2.43	3.80	4.51	2.46	1.36
R2	1.55	2.56	3.72	4.60	2.53	1.27
R3	1.60	2.40	3.92	4.23	2.63	1.78
R4	1.46	2.17	4.20	4.64	2.98	1.33
Mean	1.48	2.39	3.91	4.50	2.65	1.43
SE	0.06	0.08	0.09	0.11	0.12	0.12
CI	0.12	0.16	0.18	0.21	0.23	0.23

Where R1, R2, R3 and R4 represents replication.

Table 4.5: Variation of LAI in the wheat crop at different growth stages under irrigated condition during *rabi* season 2017-18.

Observations	Days after sowing (DAS)					
	20	40	60	80	90	120
A	0.15	1.6	2.76	2.74	5.6	3.075
B	0.12	1.7	2.54	2.734	5.82	2.8575
C	0.11	1.62	2.34	2.87	5.43	2.7375
D	0.16	1.74	2.62	2.74	5.72	2.88
Mean	0.14	1.26	2.67	2.92	5.4	2.51
SE	0.14	1.58	2.59	2.80	5.59	2.81
CI	0.01	0.08	0.07	0.04	0.08	0.09

Where A, B, C and D represents replication.

4.3 Yield attributing parameters, biomass and yield

4.3.1 Plant height

Plant height of maize crop varied in different observations during *kharif* season 2017 (Table 4.6). Data revealed that in all the growth stages plant height increases. The highest plant height (203.75 cm) was observed at 108 DAS. It was observed that plant height was increased up to 108 DAS after that it attained a stagnant stage.

Table 4.6: Variation of plant height (cm) of maize crop under irrigated condition during *kharif* season 2017.

Observations	Days after sowing (DAS)					
	30	50	60	75	90	108
R1	41.00	147.30	176.44	185.60	197.34	203.44
R2	36.50	132.00	174.92	192.19	194.60	201.92
R3	32.00	144.50	177.11	198.06	198.14	203.75
R4	33.75	138.00	174.60	188.40	197.00	202.32
Mean	35.81	140.45	175.77	191.06	196.77	202.86
SE	1.96	3.42	0.60	2.70	0.76	0.44
CI	3.84	6.71	1.18	5.28	1.49	0.86

Where R1, R2, R3 and R4 represents replication.

In *rabi* season 2017-18, the crop height increased in all the growth stages of the crop (Table 4.7). The highest (100.13cm) plant height was observed around 100 DAS. Crop height was increased upto 100 DAS.

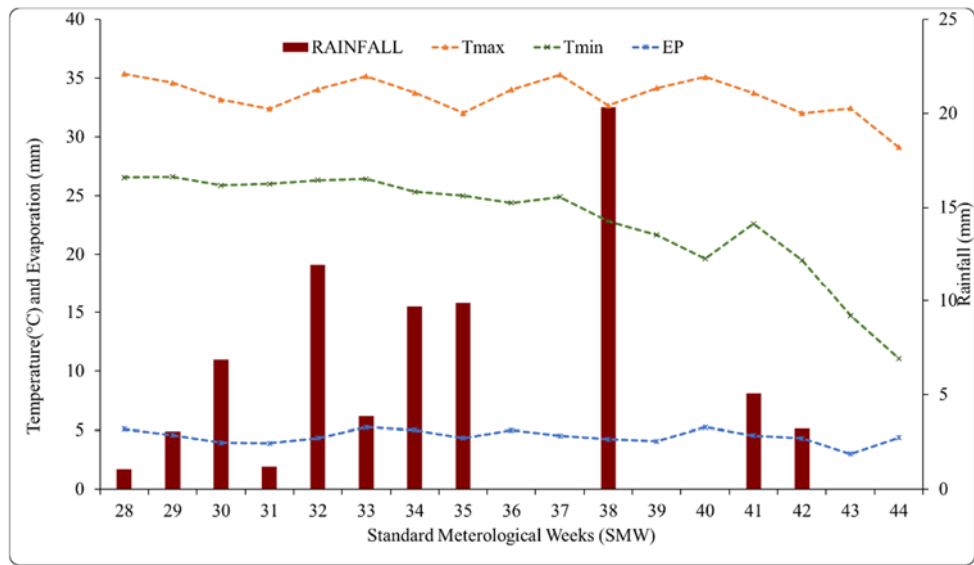


Fig. 4.1 Weekly mean maximum temperature, mean minimum temperature, evaporation and rainfall at ICAR-IARI farm during *kharif* 2017

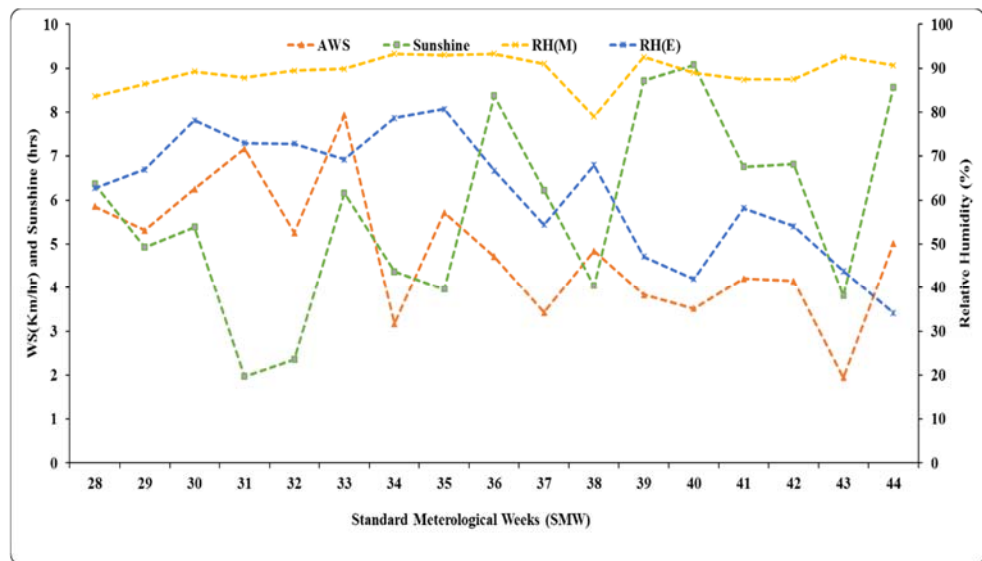


Fig. 4.2 Weekly average wind speed, sunshine hour, RH (morning & evening) in ICAR-IARI farm during *kharif* 2017

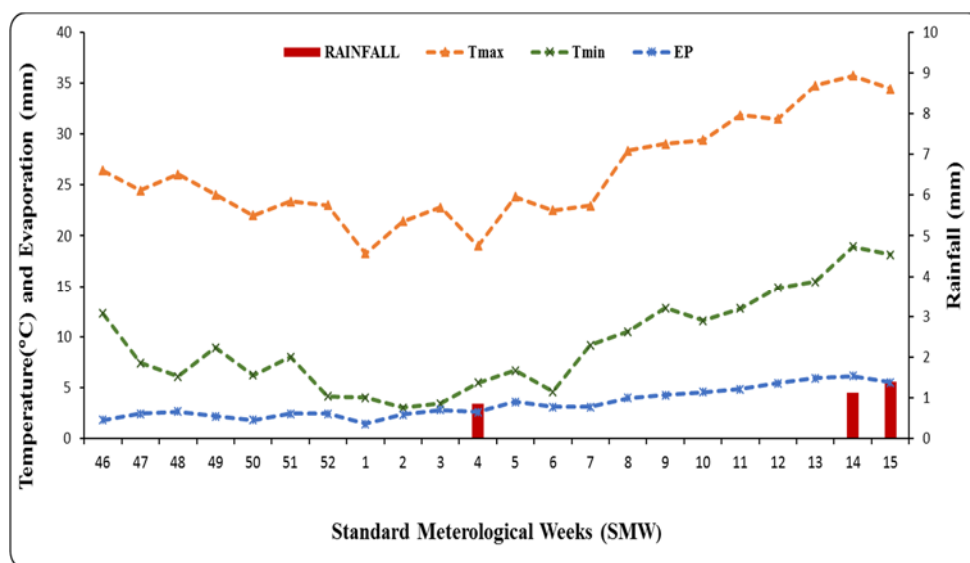


Fig. 4.3 Weekly mean maximum temperature, minimum temperature, evaporation and rainfall at ICAR-IARI farm during *rabi* 2017-18

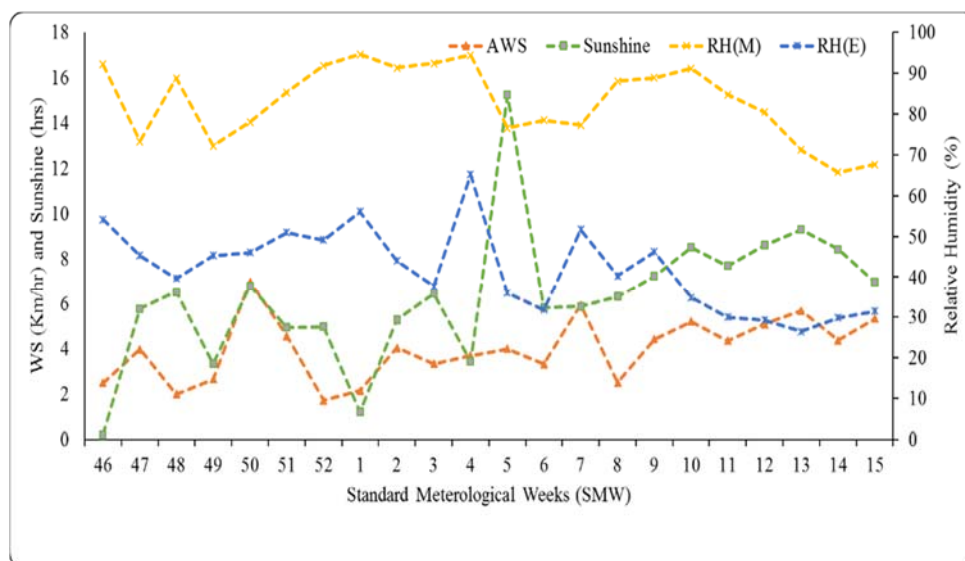


Fig. 4.4 Weekly average wind speed, sunshine hour, RH (morning & evening) in ICAR-IARI farm during *rabi*, 2017-18

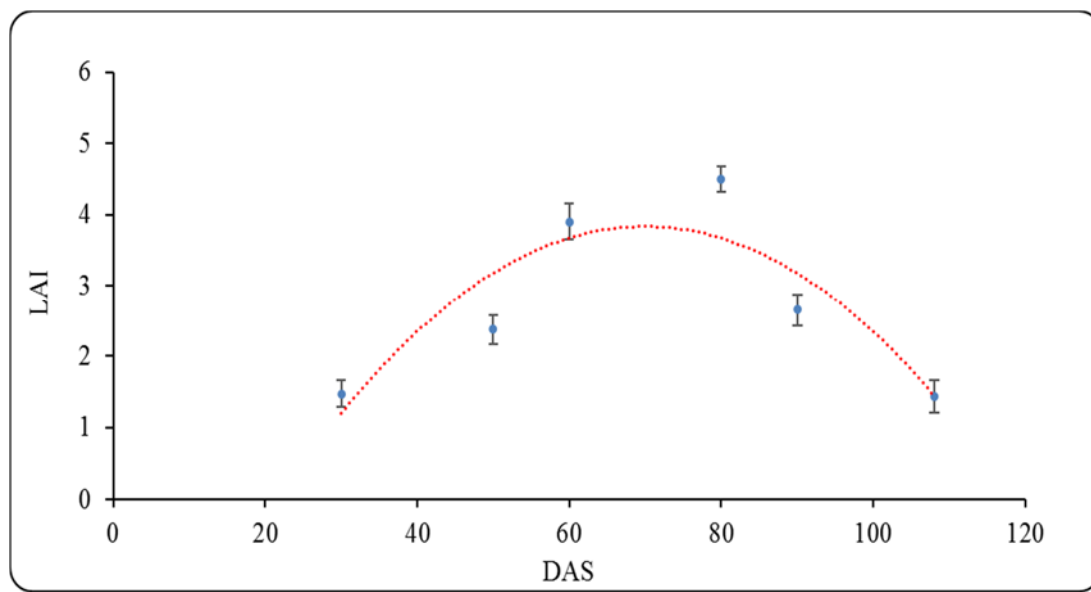


Fig. 4.5 Variation of LAI in maize crop at different growth stages under irrigated condition during *kharif* season 2017

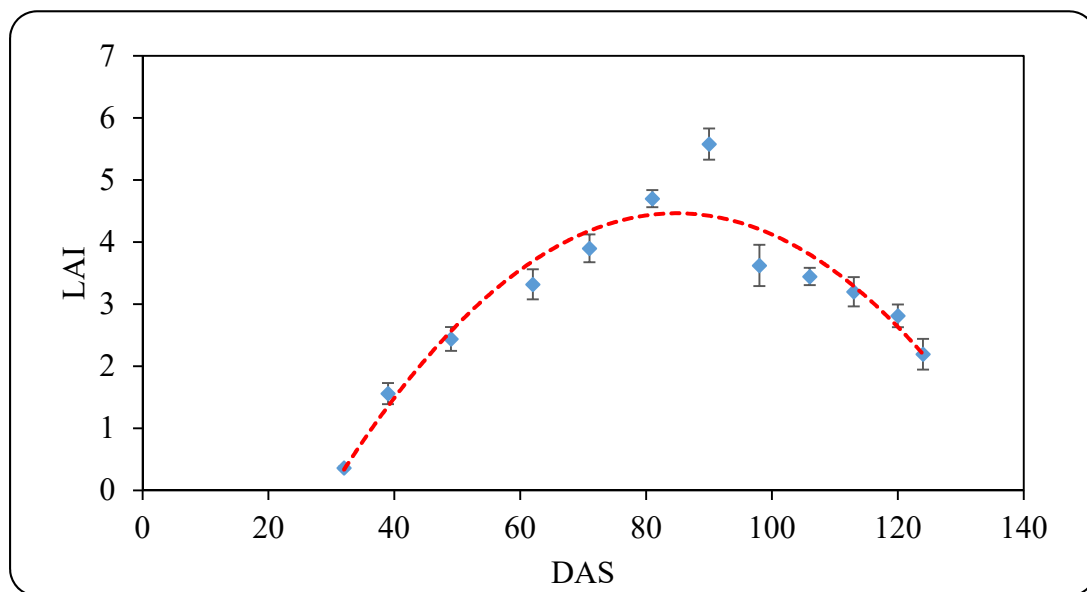


Fig 4.6 Variation of LAI in wheat crop at different growth stages under irrigated condition during *rabi* season 2017-18

Table 4.7: Variation of plant height (cm) of wheat crop under irrigated condition during *rabi* season 2017-18.

Observations	Days after sowing (DAS)					
	20	40	60	80	100	120
A	12.5	19.00	39.25	50.25	100.125	109.87
B	13.00	17.00	38.75	53.50	90.00	97.25
C	14.50	21.5	36.75	46.75	89.00	95.37
D	15.50	19.00	37.00	48.50	91.5	94.75
E	15.00	21.00	37.75	51.75	92.00	95.75
Mean	14.10	19.50	37.90	50.15	92.53	98.60
SE	0.58	0.81	0.48	1.18	1.97	2.85
CI	1.13	1.58	0.95	2.32	3.87	5.58

Where A, B, C, D and E represents replication.

4.3.2 Biomass accumulation

During *kharif* 2017, maize crop produced the highest biomass (19.27 t ha⁻¹) in 108 DAS (Table 4.8). Maximum gain in biomass accumulation was observed in between 60-90 DAS. After 108 DAS biomass accumulation was reached a plateau. Standard error varied from 0.08 to 0.50 throughout the growing season.

Table 4.8: Total crop biomass production (t ha⁻¹) in maize crop at different growth stages under irrigated condition during *kharif* season 2017.

Observations	30 DAS	60 DAS	90 DAS	108 DAS
R1	2.44	11.32	17.40	18.78
R2	2.31	10.89	16.22	19.10
R3	2.47	10.84	17.06	18.52
R4	2.32	10.34	17.15	19.27
Mean	2.38	10.85	16.96	18.92
SE	0.04	0.20	0.26	0.17
CI	0.08	0.39	0.50	0.33

Where R1, R2, R3 and R4 represents replication.

During *rabi* 2017-18, wheat crop accumulated 13.25 t ha⁻¹ in different observations. Initially, biomass accumulation was slow upto 52 DAS but after 64 DAS crop accumulated biomass rapidly. Highest biomass was observed at 117 DAS (Table

4.9). Standard error varied from 0.02 to 0.56 and confidence interval (95% probability level) varied from 0.04 to 1.10 among different observations.

Table 4.9: Total crop biomass production (t ha⁻¹) in wheat crop at different growth stages under irrigated condition during *rabi* season 2017-18.

Observations	38 DAS	45 DAS	52 DAS	64 DAS	80 DAS	117 DAS	140 DAS
A	0.46	1.81	2.00	5.42	9.20	11.42	12.67
B	0.38	1.50	2.50	4.42	8.66	12.00	12.31
C	0.42	1.46	2.30	4.56	8.30	13.00	12.36
D	0.33	1.68	2.60	3.97	8.97	10.00	13.25
E	0.39	1.56	2.20	4.30	8.52	13.00	11.15
Mean	0.40	1.60	2.32	4.53	8.73	11.88	12.35
SE	0.02	0.06	0.11	0.24	0.16	0.56	0.34
CI	0.04	0.13	0.21	0.47	0.31	1.10	0.67

(where A, B, C, D and E represents replication).

4.3.3 Yield attributes

Yield attributes of maize crop grown in *kharif* 2017 were presented in Table 4.10. Yield attributes were collected at harvest. Number of row per cob varied from 12.9 to 13.9, Number of grains per row varied from 25 to 30.1, test weight varied from 213.9 to 222.1, cob length varied from 12.9 to 13.2 and cob girth varied from 11.3 to 11.9.

Table 4.10: Yield attributes of maize crop at different growth stages under irrigated condition during *kharif* season 2017-18.

Observations	No of row/cob	No of grains/row	No of grains/cob	Test weight (g)	Cob length (cm)	Cob girth (cm)
R1	12.9	26.5	345.3	213.9	13.2	11.3
R2	13.4	25.0	344.3	214.3	12.9	11.7
R3	13.1	29.2	385.0	219.6	13.0	11.5
R4	13.9	30.1	446.2	222.1	13.0	11.9
Mean	13.3	27.7	380.2	217.5	13.0	11.6
SE	0.23	1.18	2.01	23.96	0.08	0.13
CI	0.46	2.31	3.95	46.97	0.15	0.25

Where R1, R2, R3 and R4 represents replication.

During *rabi* season 2017-18 wheat crop was grown. The data of yield attributes was presented in Table 4.11. No. of effective tillers per plant were varied from 4-5, Spike length was varied from 10.00 to 11.00 and test weight was varied from 25.84 to 27.60.

Table 4.11: Yield attributes of wheat crop at different growth stages under irrigated condition during *rabi* season 2017-18.

Observations	No of effective tillers/plant	Spike length (cm)	Test weight (g)
A	4	10.00	26.47
B	5	11.00	27.05
C	4	10.57	27.6
D	4	10.75	26.42
E	4	10.25	25.84
Average	4.20	10.51	26.68
SE	0.20	0.18	0.30
CI	0.39	0.35	0.59

Where A, B, C, D and E represents replication.

4.3.4 Grain yield and harvest index

Mean grain yield of maize crop recorded was 5.66 t ha⁻¹ during *kharif* 2017 (Table 4.12). Grain yield was varied from 5.62 to 5.75 t ha⁻¹ among all the observations. Highest stover yield recorded was 12.63 t ha⁻¹ and highest harvest index was 31.62%.

Table 4.12: Yield and harvest index of maize crop at different growth stages under irrigated condition during *kharif* season 2017-18.

Observations	Grain yield (t/ha)	Biological yield (t/ha)	Stover yield (t/ha)	Harvest index (%)
R1	5.62	18.25	12.63	30.79
R2	5.58	18.10	12.52	30.83
R3	5.70	18.03	12.33	31.61
R4	5.75	18.24	12.49	31.52
Mean	5.66	18.83	12.49	30.07
SE	0.04	0.05	0.22	0.06
CI	1.47	5.36	8.55	3.44

Where R1, R2, R3 and R4 represents replication.

During *rabi* season 2017-18, wheat grain yield varied from 4.18- 4.32 t ha⁻¹ (Table 4.13). The mean grain yield observed was 4.17 t ha⁻¹. Straw yield varied from 6.97 to 8.50 t ha⁻¹ among different observations. Highest harvest index recorded was 37.49.

Table 4.13: Yield and harvest index of wheat crop at different growth stages under irrigated condition during *rabi* season 2017-18.

Observations	Grain yield (t/ha)	Biological yield (t/ha)	Straw yield (t/ha)	Harvest index (%)
A	4.17	12.67	8.50	32.91
B	4.02	12.31	8.29	32.66
C	4.14	12.36	8.22	33.50
D	4.32	13.25	8.93	32.60
E	4.18	11.15	6.97	37.49
Mean	4.17	12.35	8.18	33.83
SE	0.05	0.34	0.33	0.93
CI	0.09	0.67	0.64	1.82

Where A, B, C, D and E represents replication.

4.4. Resource utilization efficiency

4.4.1 Radiation use efficiency (RUE)

The data on total seasonal intercepted PAR (TIPAR) and radiation use efficiency (RUE) in the account of biomass accumulation and yield of chick pea under maize crop during *kharif* season 2017 and wheat crop during *rabi* season 2017-18 are given in Table 4.14.

The TIPAR was 663.59 MJ m⁻² and 597.64 MJ m⁻² for maize and wheat crop, respectively. Radiation Use Efficiency on account of biomass accumulation was more in maize than wheat crop. The RUE on account of biomass accumulation was higher under in maize crop (2.74 g MJ⁻¹) than wheat crop (2.07 g MJ⁻¹). A similar trend was also observed in RUE_y. The RUE for yield was lower in wheat (0.70 g MJ⁻¹) in comparison to maize crop (0.85 g MJ⁻¹).

Table 4.14: Radiation use of efficiency of maize during *kharif* 2017 and wheat crop during *rabi* 2017-18.

Observations	Biomass (g/m ²)	Yield (g/m ²)	TIPAR (MJ/m ²)	RUE _b (g/MJ)	RUE _y (g/MJ)
Wheat					
A	1267	417	595.71	2.13	0.71
B	1231	402	628.13	1.96	0.64
C	1236	414	600	2.06	0.69
D	1325	432	583.78	2.27	0.74
E	1115	418	580.56	1.92	0.72
Mean	1235	417	597.64	2.07	0.70
SE	0.34	0.05	8.43	0.06	0.02
CI	0.67	0.09	16.53	0.12	0.03
Maize					
R1	1825	562	640.35	2.85	0.88
R2	1810	558	683.02	2.65	0.82
R3	1803	570	665.31	2.71	0.86
R4	1824	575	665.69	2.74	0.86
Mean	1883	566	663.59	2.74	0.85
SE	0.05	0.04	3.06	0.04	0.01
CI	5.36	1.47	0.08	0.08	0.03

Where A, B, C, D and E represents replication in wheat, and R1, R2, R3 and R4 in maize.

4.4.2 Soil moisture

The variation in profile soil moisture content in maize (*kharif*, 2017) and wheat (*rabi*, 2017-18) crops are shown in Fig. 4.7 and 4.8. The soil moisture varied throughout the crop growing season. Initially, it was low but during whole season it varied around 15% in all three depths.

On 21 DAS the crop received 61 mm of rainfall and the soil moisture increased after that. The soil moisture at 15 cm depth is always more than other two depths (5 cm and 25 cm). On 24th August, 2017 (37 DAS) crop received 61.4 mm of rainfall and soil increased to 24.14% at 15 cm depth. On 1st September, 2017, the crop received another 45.6 mm of rainfall and the soil moisture of 15 cm depth recorded 26.88%. On 23rd September, 2017 the crop received 136.8 mm of rainfall. The soil moisture at 15 cm depth reached upto 29.69% and remain around 20% for 3-4 days. Later stage of the crop, there was no rainfall event and at harvest, soil was almost dry and the moisture was 10.36% at 15cm depth.

In *rabi*, 2017, not even a single rainy day was observed. A total of 3.37 mm rainfall was recorded but no rainy day was there, only 15th week received 1.5mm rainfall. The crop was grown in under irrigation. The peak of the soil moisture observed after irrigation only. Soil moisture was more at 15cm soil depth compare to 5 cm and 25 cm.

4.5. Micrometeorology inside crop canopy

4.5.1. Maize crop

4.5.1.1 Wind profile

Wind data inside the maize crop canopy were collected during *kharif* season 2017 in 10 minutes interval throughout the growth period. Data of wind profile of different phenological stages were presented in Fig 4.9a and Fig 4.9b. At the time of sowing (20th July, 2017) lowest wind speed was at night time. In general wind speed was increasing with increases in height of the sensor. Highest wind speed was recorded with the sensor installed at 8 m. In night wind speed was ranged from 0.208 to 0.63 m sec⁻¹ whereas morning wind speed was varied from 1.85 to 3.13 m sec⁻¹. Slightly more wind speed was recorded in morning compare to evening and noon time wind speed was ranged from 1.27 to 1.96 m sec⁻¹.

For 4 leaf stage also wind speed was increasing with height. Highest wind speed was recorded as 2.52 to 4.125 m sec⁻¹ on 01st July 2017 with the sensor installed at 8m. Low wind speed values ranged from 0.68 to 1.41 m sec⁻¹ were recorded in the night. The wind speed observed slightly more during morning and noon time.

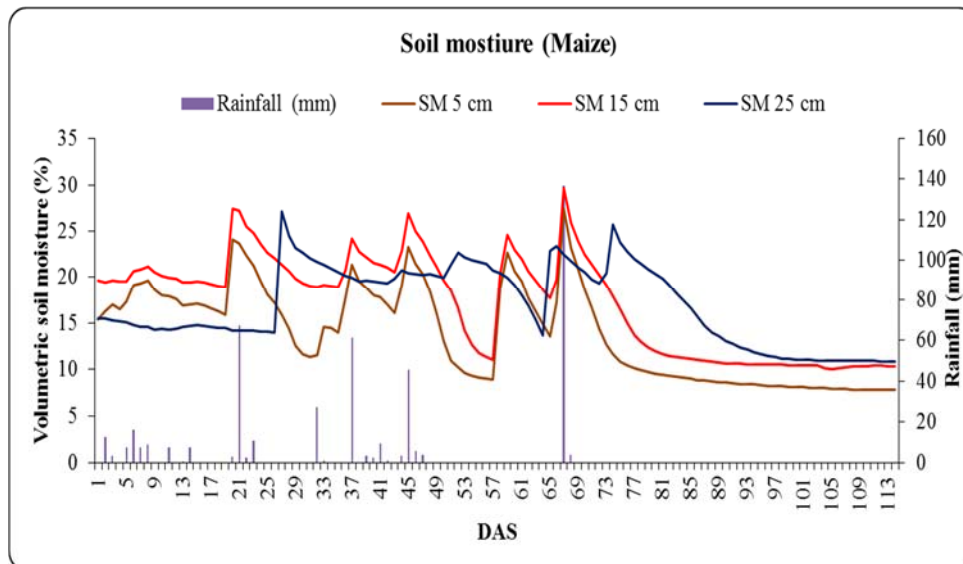


Fig. 4.7 Variation of soil moisture in maize crop (*kharif*, 2017)

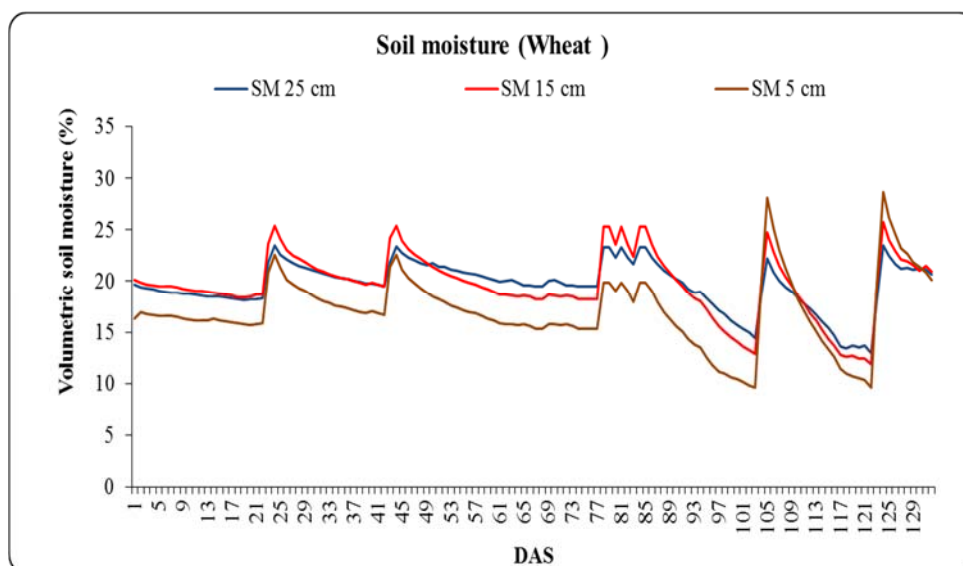


Fig. 4.8 Variation of soil moisture in wheat crop (*rabi*, 2017-18)

At 5 leaf stage, the trend of wind speed seemed increasing with sensor installed height with highest values ranged from 1.64 to 2.87 m sec⁻¹ during morning time. While the low values ranging from 0.14 to 0.64 m sec⁻¹ observed in the night.

For 6 leaf stage, the night time recorded highest wind speed values ranged from 1.87 to 3.77 m sec⁻¹ with the sensor installed at height of 8m whereas lowest values of 0.64 to 1.18 m sec⁻¹ obtained in evening. In knee high stage, the noon followed a high wind speed values ranging from 0.79 to 4.06 m sec⁻¹ while low values ranging from 0.27 to 2.31 m sec⁻¹ observed in the night.

At tasselling stage, highest wind speed values were recorded during evening time with a range from 0.25 to 3.75 m sec⁻¹. While very low values ranged from 0 to 0.47 m sec⁻¹ were recorded in the night. In silking stage, the noon time showed a highest wind speed values ranging from 0.06 to 1.68 m sec⁻¹ whereas low values similar to tasselling stage observed here also.

At dough stage, the highest values ranged from 0.02 to 2.41 m sec⁻¹ recorded in evening at sensor height of 8m. In the night, lowest values with a range of 0 to 0.29 m sec⁻¹ followed a constant trend up to sensor installed at 8m height. For grain maturity stage, the wind speed values showed an increasing trend with highest values ranging between 0.16 to 1.8 m sec⁻¹ during noon.

4.5.1.2 Temperature profile

Temperature data values within the maize crop canopy were collected for an interval of 10 minutes during the crop growth period of the year 2017. Temperature profiles for different phenological stages of the crop were shown in Fig. 4.10a and Fig. 4.10b. During sowing stage, temperature values increased with the sensor installed height in all the data collection period of time. The highest values (32.81 to 32.3 °C) observed in evening whereas comparative lowest value (24.66 to 24.73 °C) found during morning time.

At 4 leaf stage, the highest values ranged from 29.34 to 29.14 °C recorded in evening while lowest temperature values from 26.52 to 26.78 °C observed during morning time.

At 5 leaf stage, noon and evening time with high values initially followed decreasing trend till 4m, afterward it became constant up to 8m of installed sensor height. Lowest temperature values recorded in morning with a range of 28.27 to 28.15

°C. In 6 leaf stage, the evening recorded slight high temperatures ranged from 33.75 to 33 °C while low temperature values ranged from 28.01 to 28.05 °C observed in morning.

At knee high stage, the temperature values were found high as 31.9 °C with sensor installed at low height but followed slightly decreasing trend having 31.04 °C with sensor height at 8m in evening. The morning recorded low temperature values ranged from 27.69 to 27.64 °C followed a similar pattern as in evening. In tasselling stage, noon and evening temperature values were found close. Similarly, night and morning values seemed very close to each other. The highest values ranged from 34.28 to 33.01 °C recorded in evening.

At silking stage, the temperature values followed a similar trend as in tasselling stage. In dough stage, the temperature values in evening found ranged from 35.21 to 35.09 °C as the highest one. While morning time showed lowest values of 17.34 to 19.8 °C. The grain maturing stage recorded highest values ranging from 29.71 to 27.71 °C in noon whereas low values of 1.09 to 21.35 °C observed in the night.

4.5.1.3 Humidity profile

For *kharif* season of the year 2017, relative humidity data values within the maize crop canopy were collected for an interval of 10 minutes throughout the crop growth period. Relative humidity profile for different phenological stages of the crop was shown in Fig. 4.11a and Fig. 4.11b. At the time of sowing, the highest RH values recorded in morning with a range of 94.08 to 91.80% where low values found in evening. In 4 leaf stage, the percentage of relative humidity values formed a cluster in all the collection time among which the night recorded the highest percentage values range from 95.488 to 93.18%. For 5 leaf stage, the night recorded highest percentage of RH values ranged from 75.87 to 75.36% while lowest (58.72 to 59.03%) observed in the evening time. In 6 leaf stage, the RH % increases with different height at which the sensors installed with highest values observed during morning time ranged from 68.91 to 66.66%. Low values recorded in the evening that fell between 60.82 to 58.11% ranges. The RH% values observed in knee-high stage during the evening and noon time was almost close to each other while the highest % ranged from 88.93 to 87.75 recorded in morning.

For tasselling stage, the night and morning RH% values initially increased up to 1m, afterwards it decreases to 81.76 RH% and 89.29 RH % till 8m. The morning

recorded the highest RH% values amongst them. On the other hand, 58.31 to 58.41 RH% were observed during the evening. In silking stage also, the initial trend of morning and night were found similar to tasselling stage with highest % values recorded in morning. Likewise, the evening RH% values decreased with increase in height from 0.5 to 4m height, afterward the values become constant up to 8m.

For dough stage, night and morning RH % showed increasing trend from 83.25 to 96.15 RH % and 81.152 to 98.76 RH % till 1m of sensor height, afterward a sudden decreasing trend was found up to 4m and later become constant up to 8m. Similarly, RH % values at noon followed the identical trend. However, in evening, the RH% values initially decreased (31.07 to 26.41 RH %) at a sensor height from 0.5 to 1m, afterward follow an unvaried trend up to 8m. Grain maturity stage showed that the RH % trend of noon and evening seemed similar to RH % trend of night and morning of dough stage. However, the gradual decreasing trend (92.97 to 86.32 RH %) observed during the morning.

4.5.2 Wheat crop

4.5.2.1 Wind profile

Wind data inside the wheat crop canopy were collected during *rabi* season 2017 in 10 minutes interval throughout the growth period. Data of wind profile of different phenological stages were presented in Fig. 4.12a and Fig. 4.12b. At the time of germination stage (25th Nov to 2017), the lowest wind speed was at night time. In general wind speed was increasing with increases in height of the sensor. Highest wind speed was recorded with the sensor installed at 8 m. In night wind speed was ranged from 0.208 to 0.375 m sec⁻¹ whereas morning wind speed was varied from 0.04167 to 0.625 m sec⁻¹. Slightly more wind speed was recorded in noon in comparison to evening and noon time wind speed, with a range of 1.27 to 1.96 m sec⁻¹. In CRI also wind speed was increasing with height. Highest wind speed was recorded as 2.7 to 4.25 m sec⁻¹ on 18st Dec 2017 with the sensor installed at 8m. Low wind speed values ranged from 1.25 to 2.42 m sec⁻¹ were recorded in the night at lowest sensor height of 0.5meters. The wind speed observed slightly more during evening and noon time.

At tillering stage, the trend of wind speed seemed increasing with sensor installed height with highest values ranging from 2.3 to 4.56 m sec⁻¹ during evening time. While the low values ranging from 0.15 to 0.79 m sec⁻¹ observed in night. For

booting stage, the recorded highest wind speed values ranged from 0.43 to 2.09 m sec⁻¹ with the sensor installed at height of 8m whereas lowest values of 0.01 to 0.75 m sec⁻¹ obtained in evening.

At flowering, the evening followed a high wind speed values ranging from 1.53 to 4.10 m sec⁻¹ while low values ranging from 0 to 0.42 m sec⁻¹ observed in night. For grain filling stage, highest wind speed values were recorded during evening time ranging from 1.43 to 4.60 m sec⁻¹. While very low values ranged from 0.20 to 1.60 m sec⁻¹ were recorded in morning. In milking stage, the evening time showed highest wind speed profile values ranging from 1.31 to 4.00 m sec⁻¹ whereas low value profile ranging from 0.01 to 0.65 in the evening with sensor height 0.5 and 8m respectively.

At dough stage, the highest values ranging from 1.70 to 5.00 m sec⁻¹ were recorded in evening at sensor height of 0.5 and 8m respectively. In the morning, lowest values of wind speed with a range of 0.12 to 1.23 m sec⁻¹ also followed a constant increasing trend from 0.5m to 8m. For maturity stage of wheat, the wind speed values showed an increasing trend with highest values with wind profile range between 0.77 to 2.3 m sec⁻¹ during evening and lowest range of 0.006 to 0.43 m sec⁻¹ during morning.

4.5.2.2 Temperature profile

Temperature data values within the wheat crop canopy were collected for an interval of 10 minutes during the crop growth period of the year 2017-18. Temperature profiles for different phenological stages of the crop were shown in Fig. 4.13a and Fig. 4.13b. During germination stage, diurnal temperature range was observed to be maximum in lower sensor height of 0.5m. The highest values (24.94 °C at 8m to 25.21 °C at 0.5m) observed in evening specifically at lower sensor height whereas comparatively lower value (7.76 °C at 0.5m to 10.62 °C at 8m) was found during morning time. In CRI, the highest values ranged from 21.38 °C (0.5m) to 21.55 °C (8m) recorded in evening while lowest temperature values from 8.39 °C (0.5m) to 12.07 °C (8m) observed during night time.

At tillering stage, noon and evening time show high temperature and almost same temperature values at different heights while morning and night showed lower temperature range with a decreasing trend as we go down from 8m to 0.5m. Lowest temperature values were recorded during morning with a range of 2.28 °C (at 0.5m) and 5.69 °C (at 8m). In booting stage, the evening recorded slight high temperatures ranging

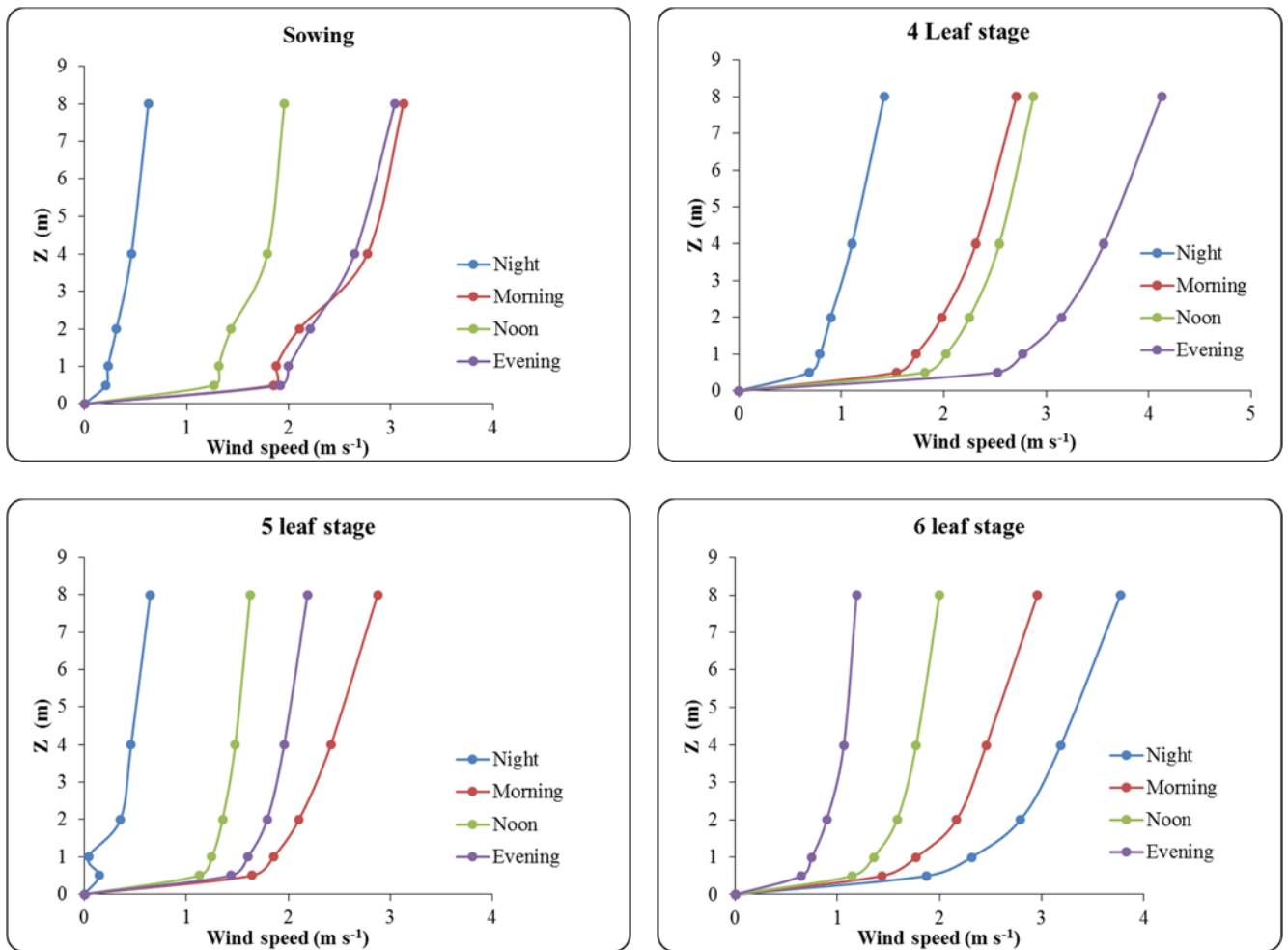


Fig 4.9a Variation of wind speed with height (wind profile) over maize crop at sowing, 4 leaf stage, 5 leaf stage and 6 leaf stage during *kharif*, 2017

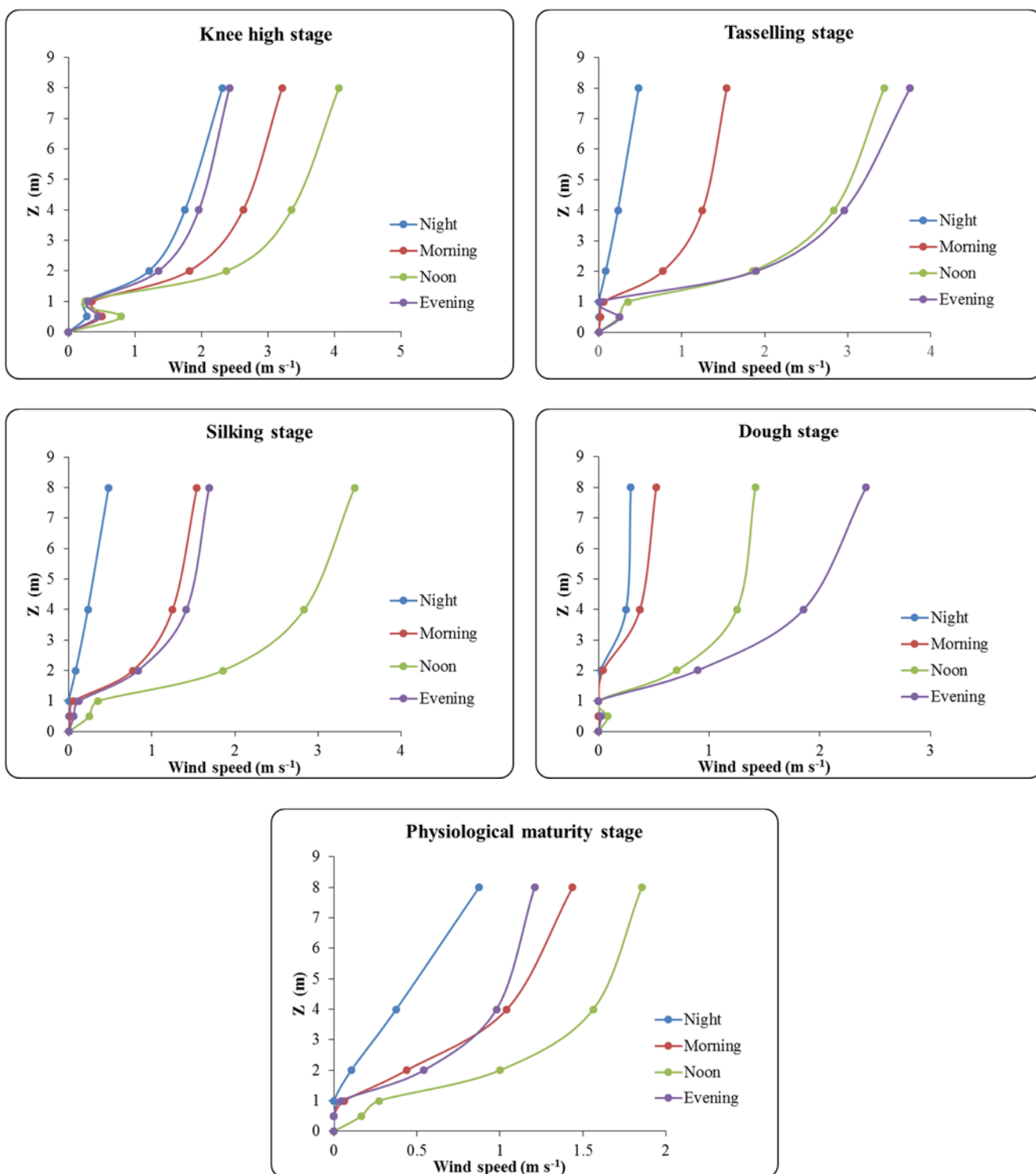


Fig 4.9b Variation of wind speed with height (wind profile) over maize crop at knee high stage, tasseling stage, silking stage, dough stage and physiological maturity stage during *kharif*, 2017

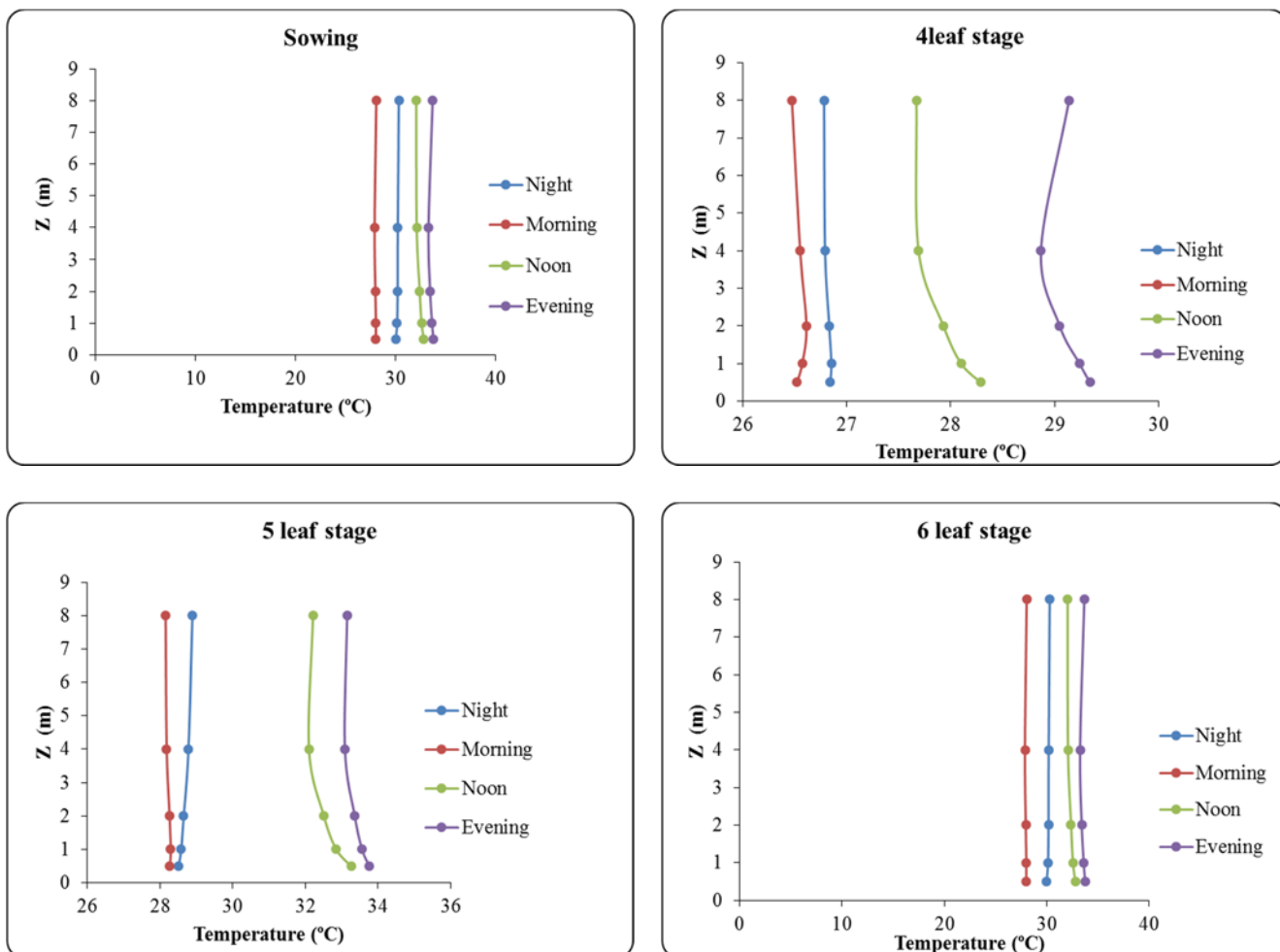


Fig.4.10a Variation of temperature with height (temperature profile) over maize crop at sowing, 4 leaf stage, 5 leaf stage and 6 leaf stage during *kharif*, 2017

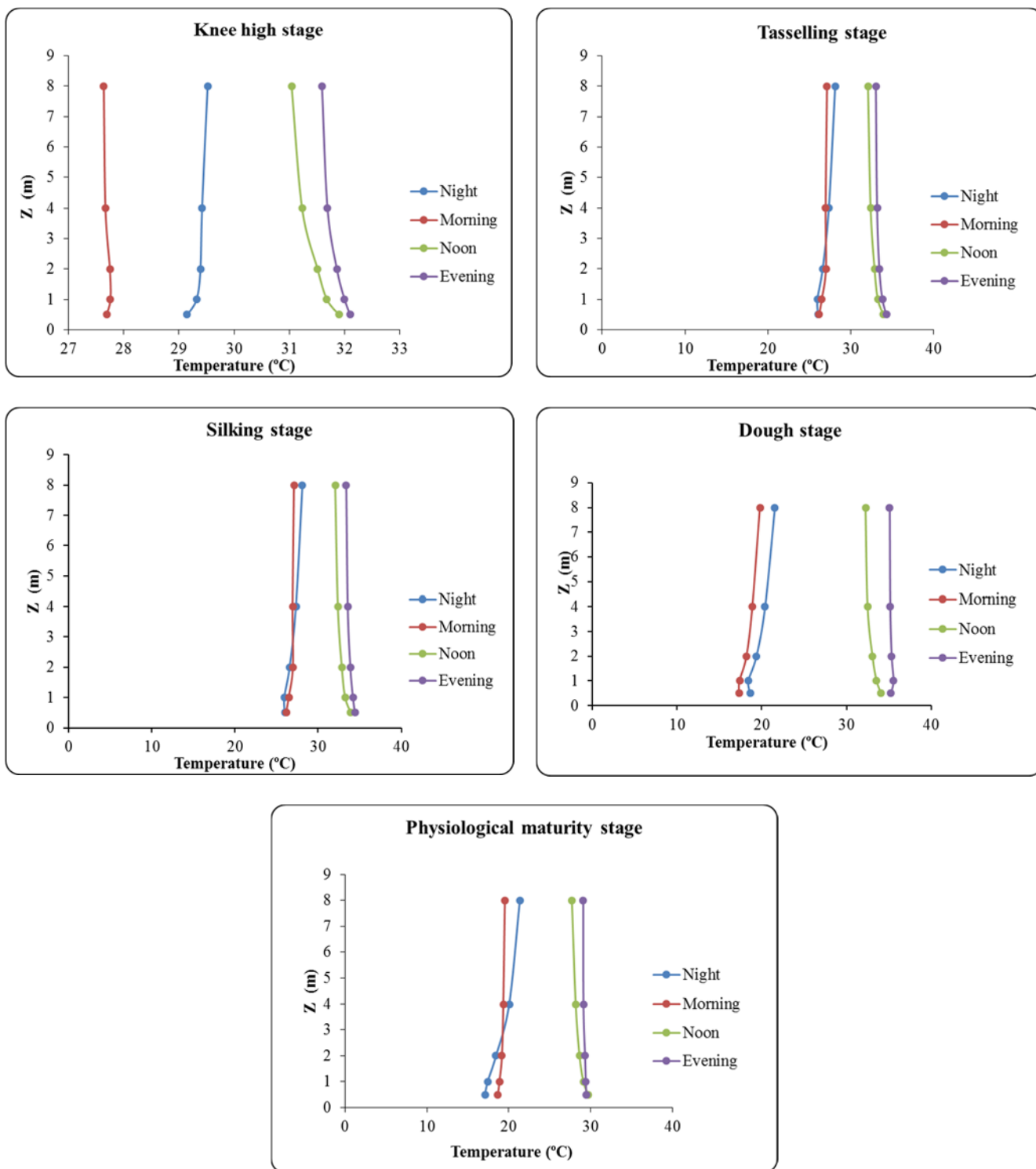


Fig 4.10b Variation of temperature with height (temperature profile) over maize crop at knee high stage, tasseling stage, silking stage, dough stage and physiological maturity during *kharif*, 2017

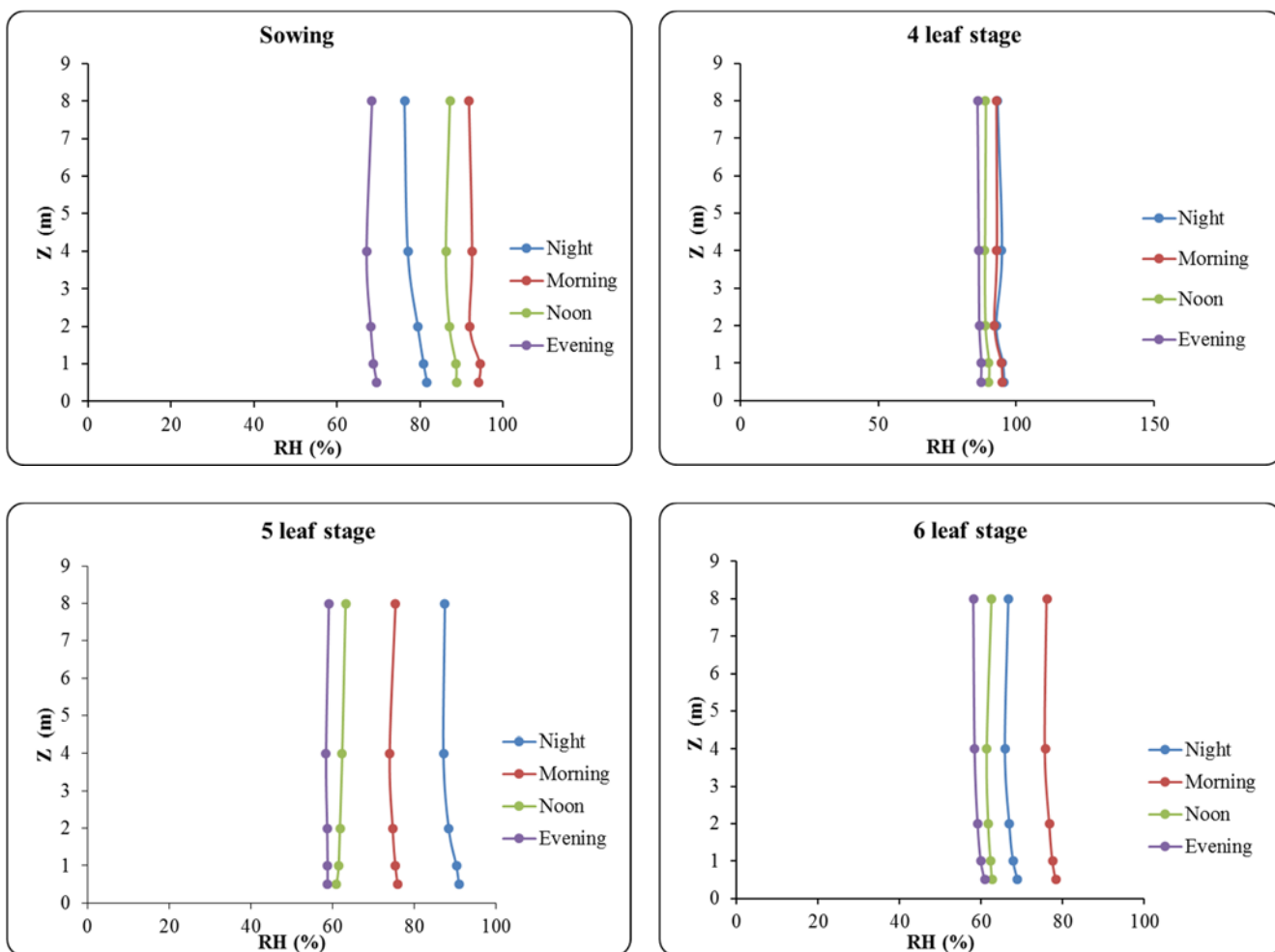


Fig 4.11a Variation of humidity with height (humidity profile) over maize crop at sowing, 4 leaf stage, 5 stage and 6 leaf stage during *kharif*, 2017

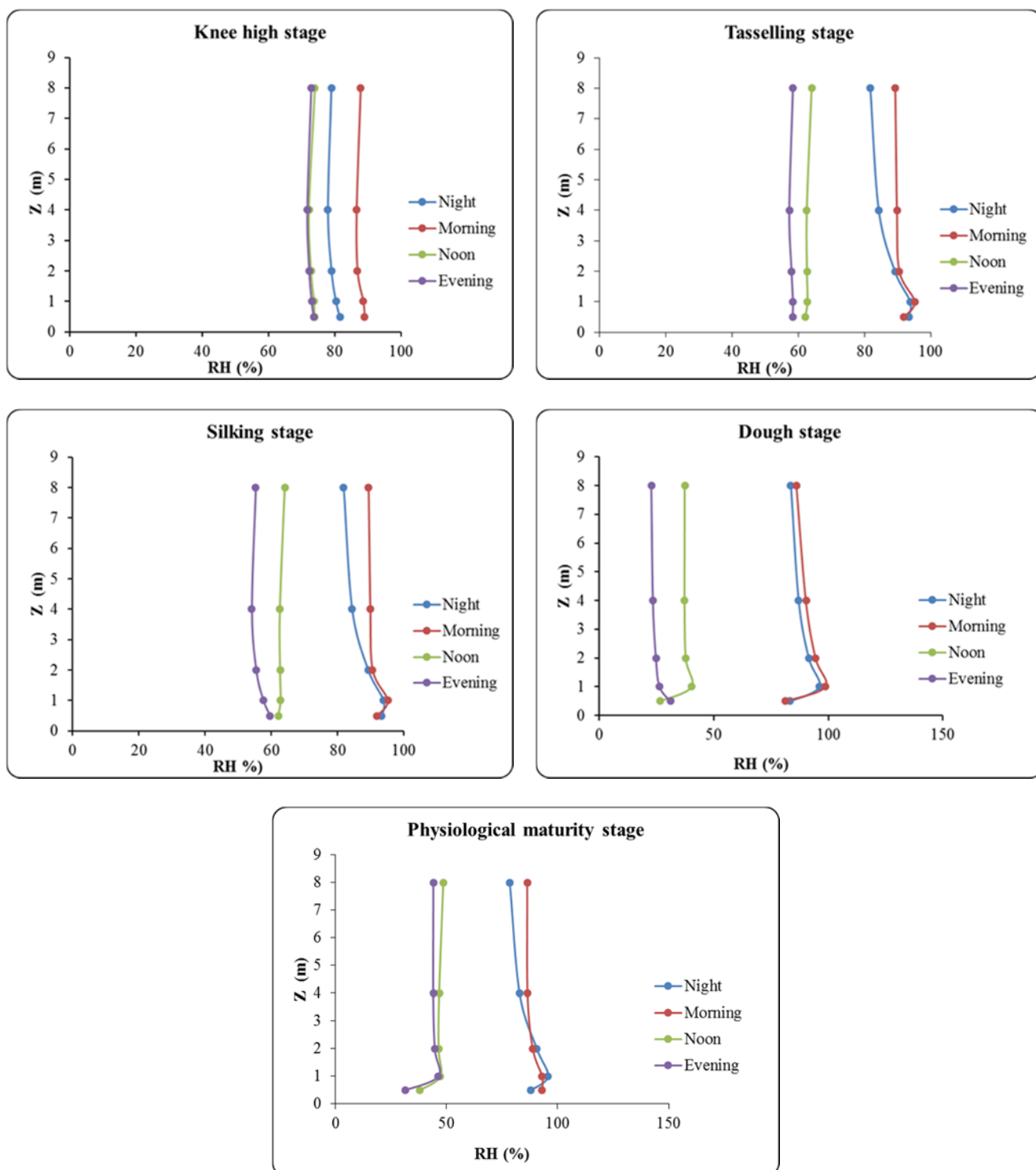


Fig 4.11b Variation of humidity with height (humidity profile) over maize crop at knee high stage, tasselling, silking stage, dough stage and physiological maturity during *kharif*, 2017

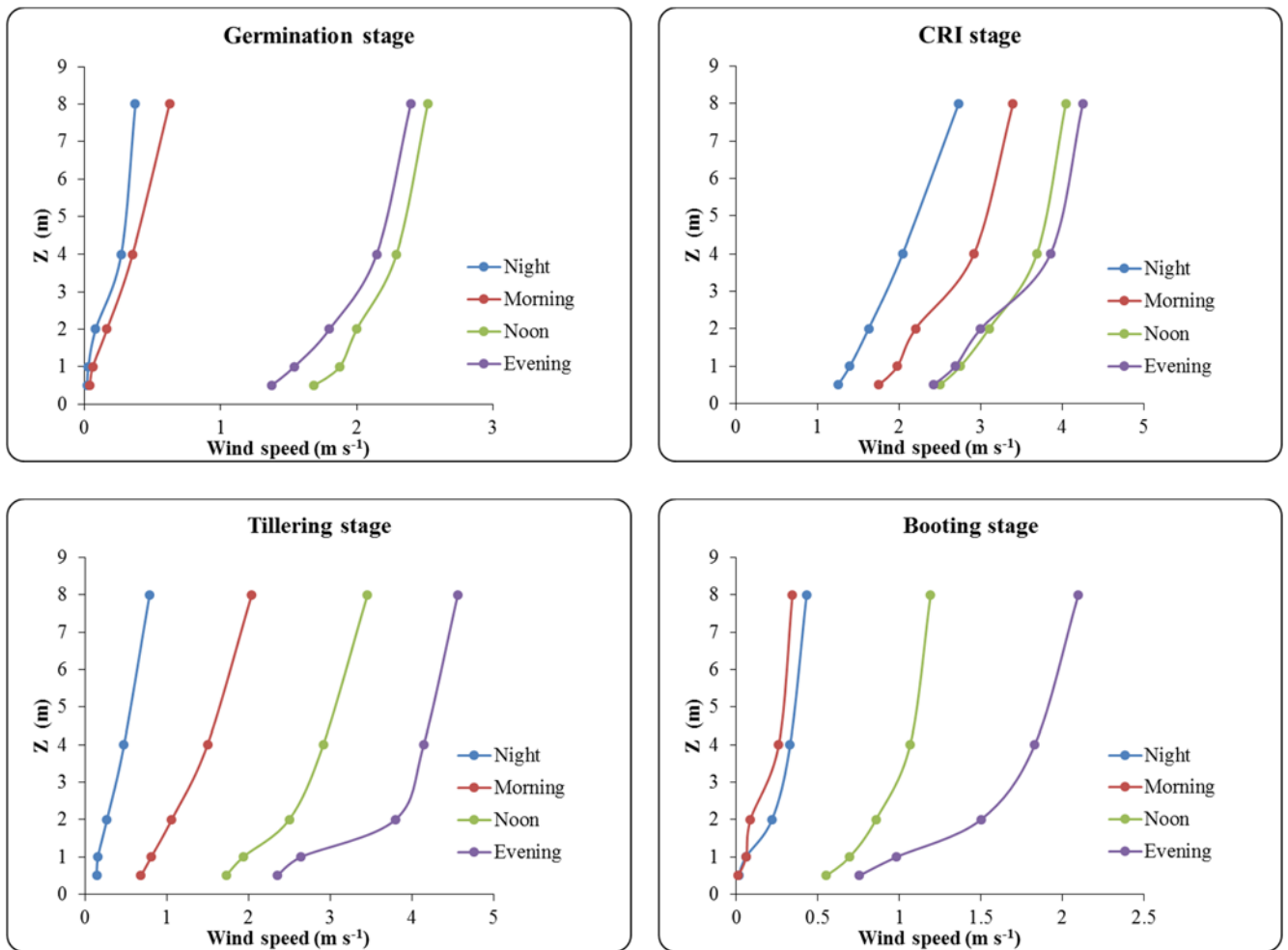


Fig 4.12a Variation of wind speed with height (wind speed profile) over wheat crop at germination stage, CRI stage, tillering stage and booting stage during *rabi*, 2017-2018

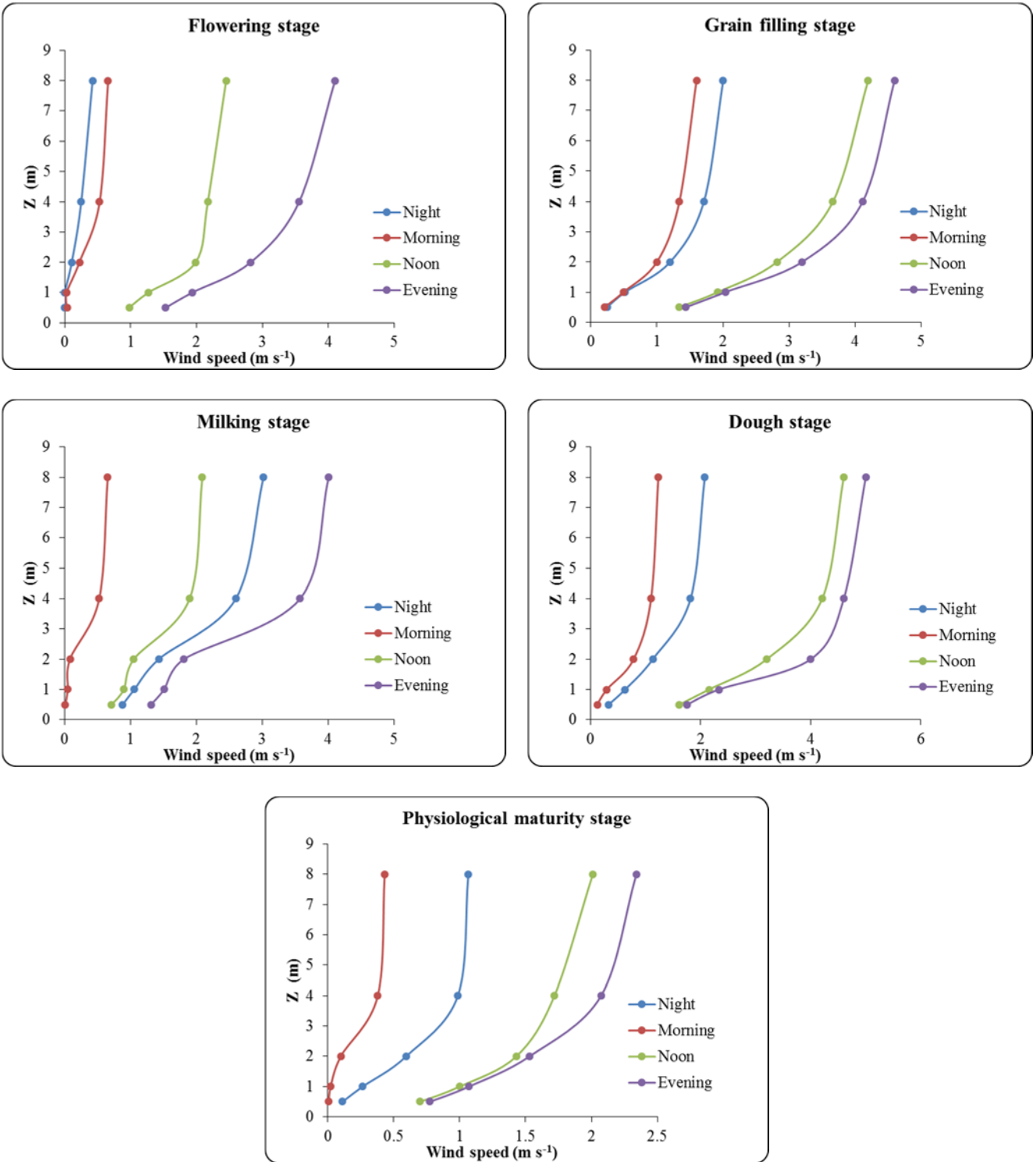


Fig 4.12b Variation of wind speed with height (wind speed profile) over wheat crop at flowering stage, grain filling stage, milking stage, dough stage and physiological maturity during *rabi*, 2017-2018

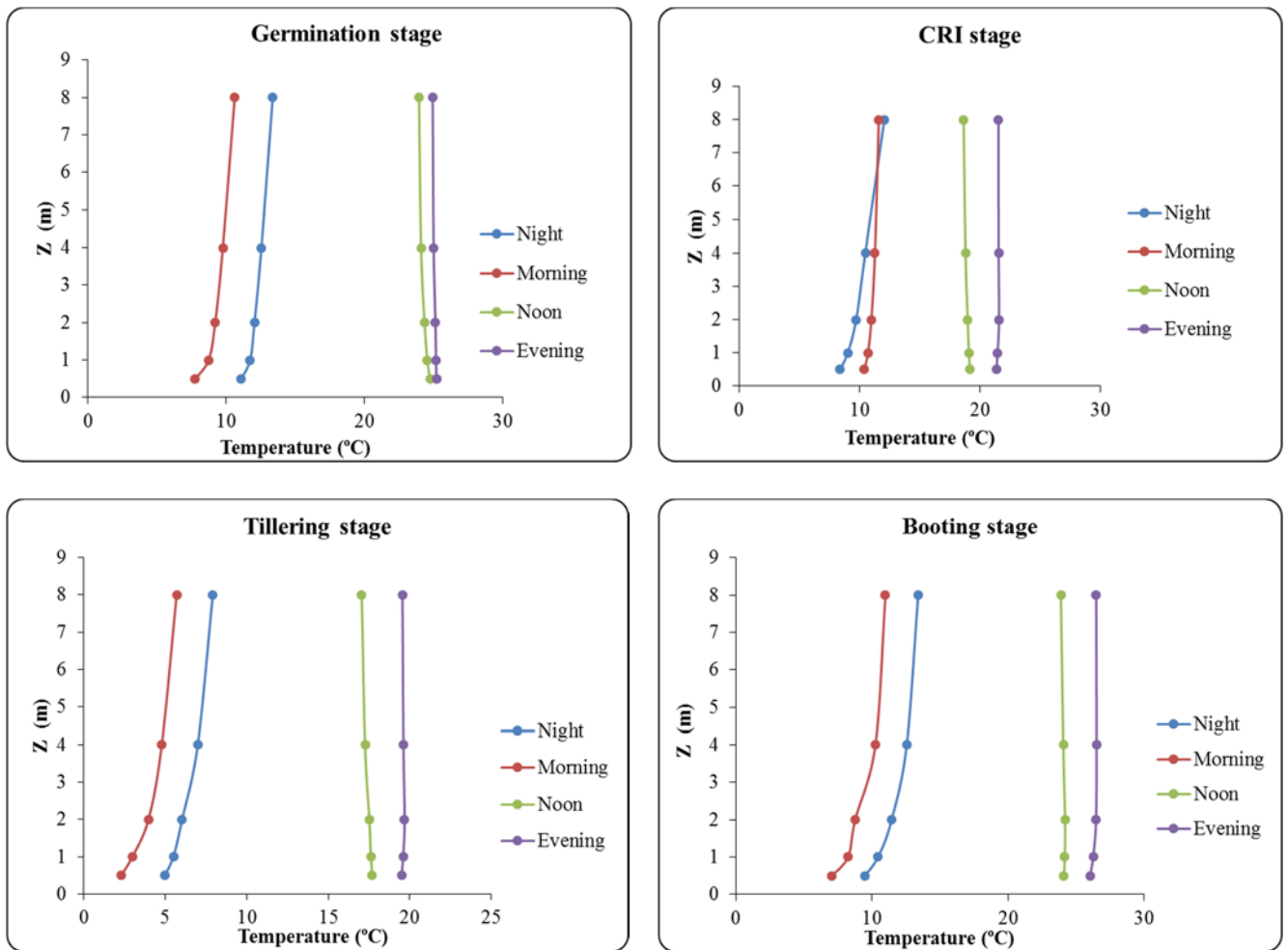


Fig 4.13a Variation of temperature with height (temperature profile) over wheat crop at germination stage, CRI stage, tillering stage and booting stage during *rabi*, 2017-2018

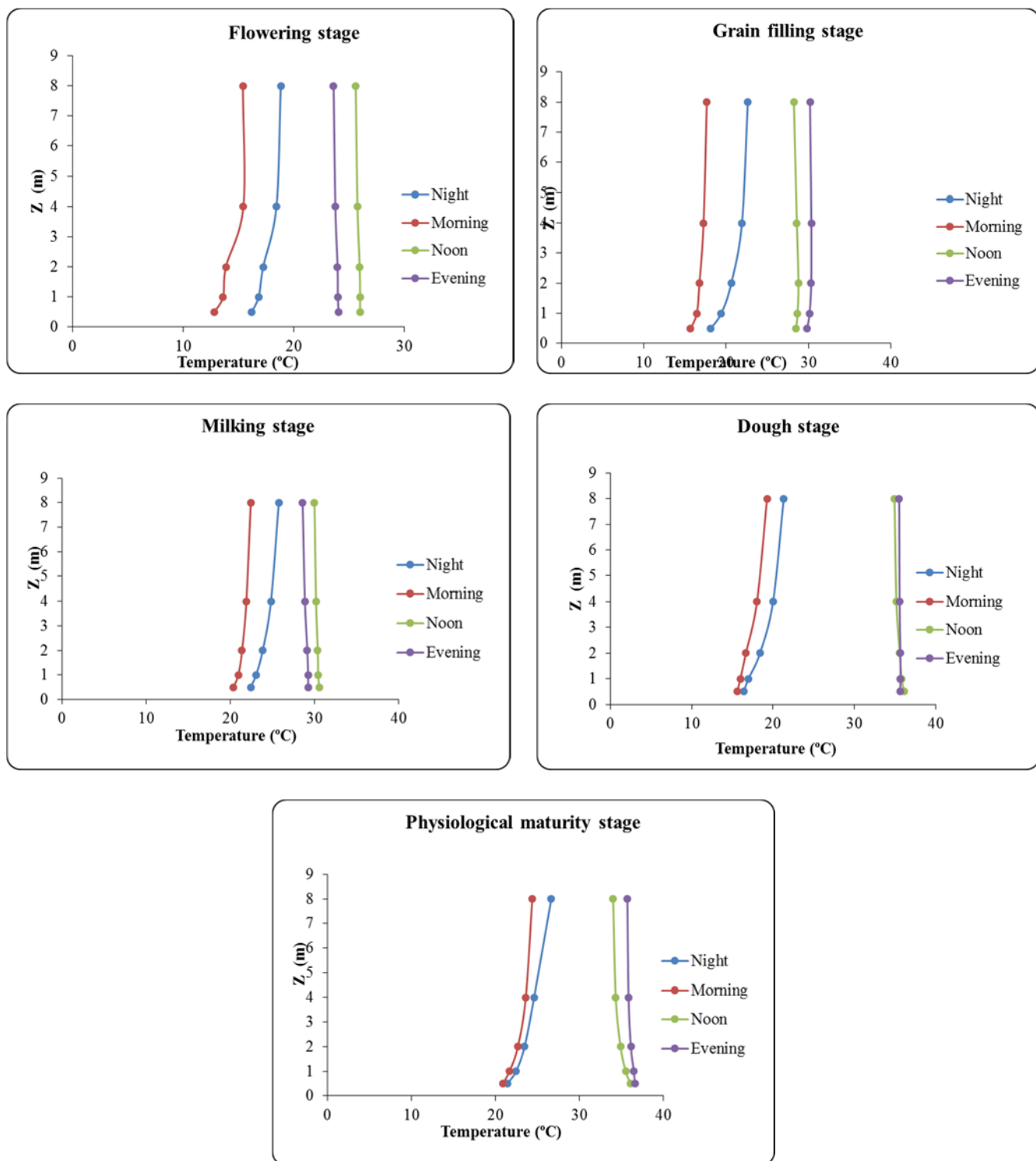


Fig 4.13b Variation of temperature with height (temperature profile) over wheat crop at flowering, grain filling stage, milking stage, dough stage and physiological maturity during *rabi*, 2017-2018

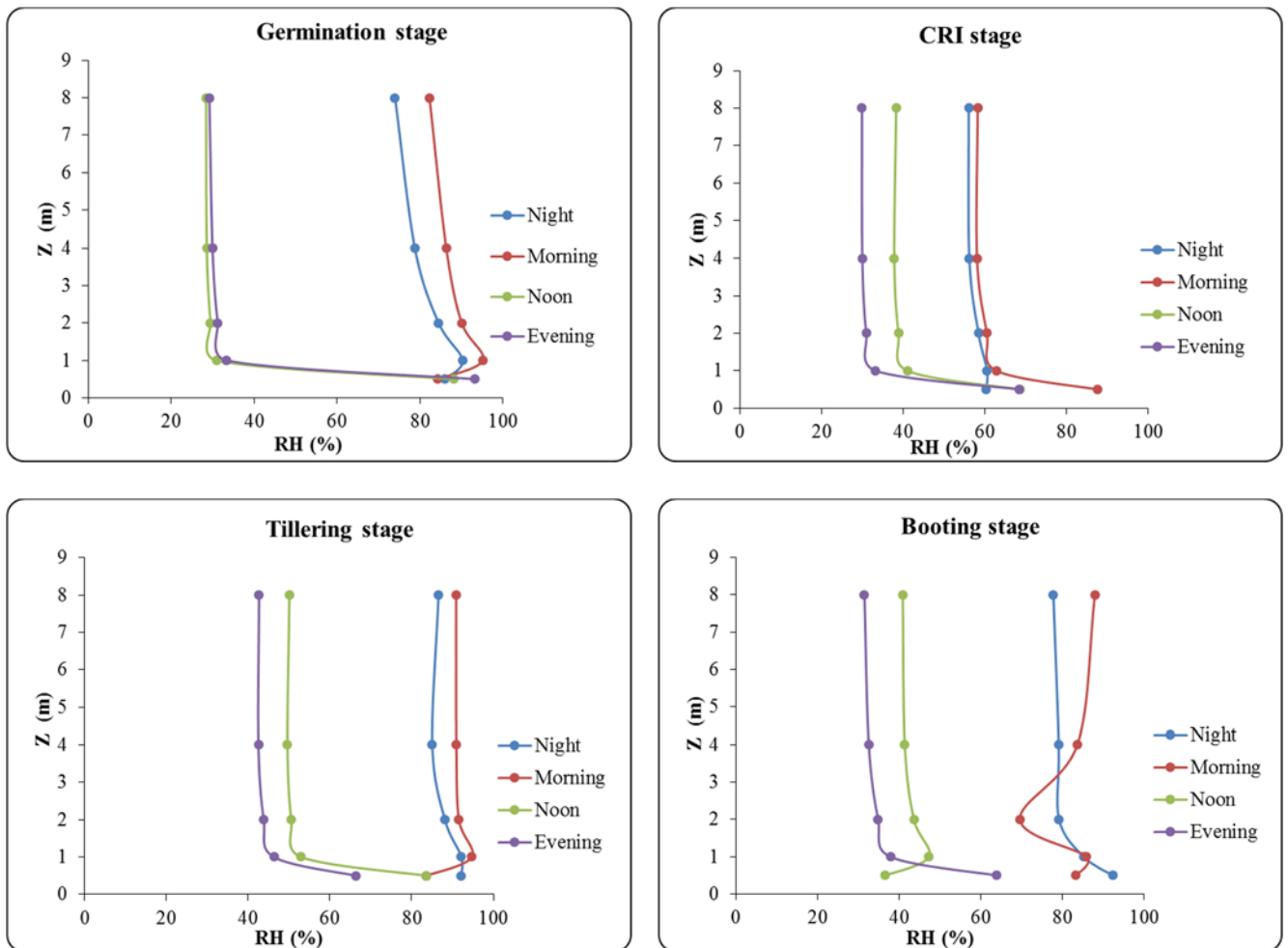


Fig 4.14a Variation of humidity with height (humidity profile) over wheat crop at germination stage, CRI stage, tillering stage and booting stage during *rabi*, 2017-2018

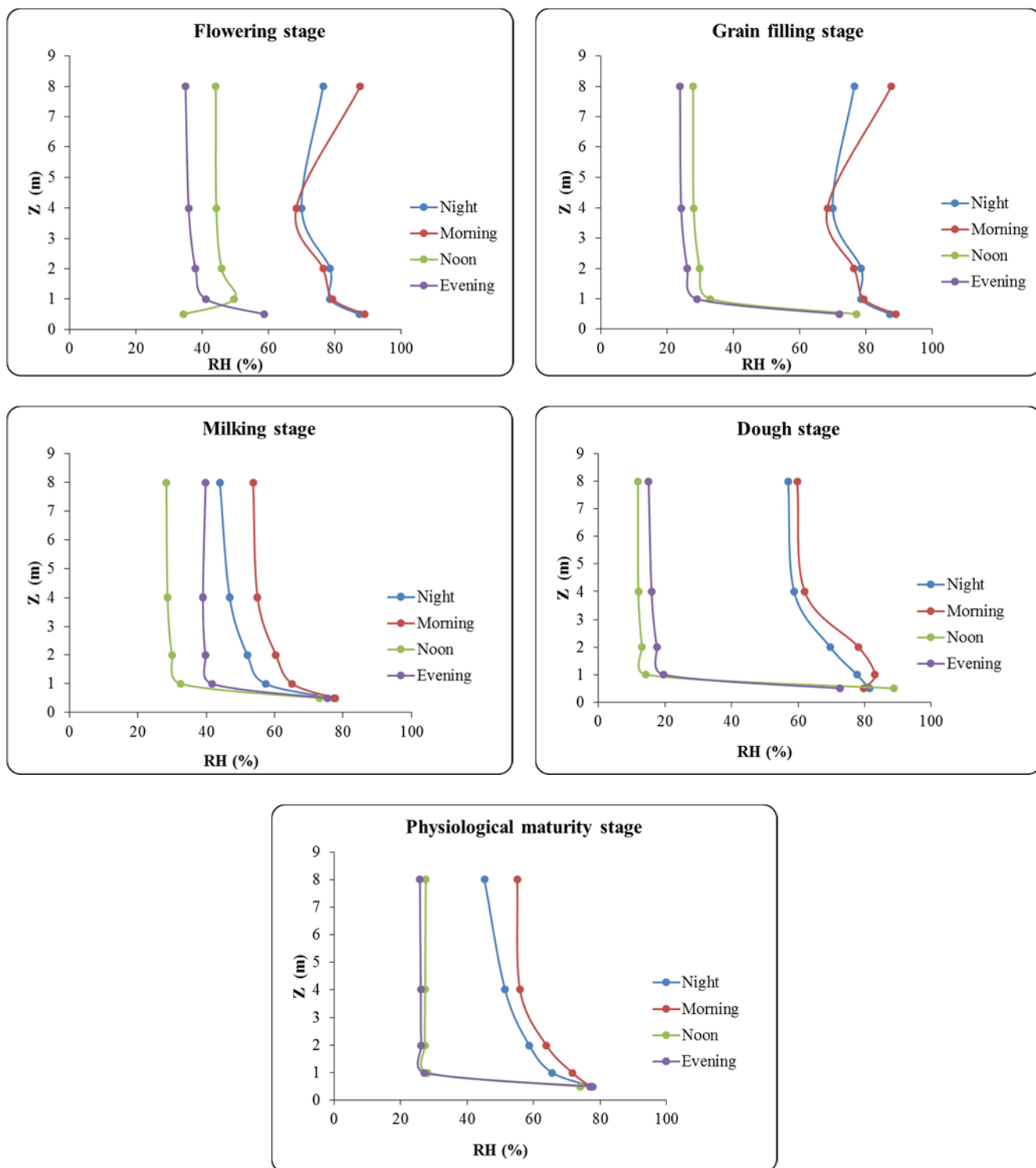


Fig 4.14b Variation of humidity with height (humidity profile) over wheat crop at flowering stage, grain filling stage, milking stage, dough stage and physiological maturity during *rabi*, 2017-2018

from 26.02 °C (at 0.5m) and 26.47 °C (at 8m) while low temperature values ranged from 7.05 to 10.99 °C observed in morning.

For the flowering stage, the temperature values were found as high as 26.00 °C in noon with the sensor installed at low height but followed slightly decreasing trend having 24.06 °C in evening. The morning recorded low temperature values ranged from 12.82 to 15.41 °C at 0.5 and 8 m respectively.

At grain filling stage, the diurnal variation pattern was characterized by highest recorded evening temperatures with a range of 29.85 to 30.19 °C. Morning period was characterized by lowest temperature recorded which range from 15.67 to 17.66 °C and night showed a range of 18.12 to 22.64 °C with the lower temperature recorded at the surface. The noon temperature ranged from 28.51 to 28.23 °C. For milking stage, lower temperature were recorded in the morning with a range of 20.36 to 22.44 °C, with the lower limit of the range recorded near the surface. In dough stage, the temperature values were higher for evening and noon with the almost same temperature at a different height. While morning time showed lowest values of 15.59 (at 0.5m) to 19.26 °C. The grain maturing stage recorded highest values ranging from 36.60 to 35.72 °C in noon whereas low values of 20.89 to 24.39 °C observed in morning.

4.5.2.3 Humidity profile

For *rabi* season of the year 2017-18, relative humidity data values within and above the wheat crop canopy were collected for an interval of 10 minutes throughout the crop growth period. Relative humidity profile for different phenological stages of crop were shown in Fig. 4.14a and Fig. 4.14b. At the time of sowing, the highest RH values recorded in morning with range of 93.28 to 29.18%, whereas low values found in noon. In CRI stage, the percentage of relative humidity values formed a cluster in all the collection time among which the morning recorded a highest percentage values range from 87.55 to 58.27%.

At tillering stage, the morning recorded highest percentage of RH values ranged from 83.56 to 90.88% while lowest (66.41 to 42.65%) observed in evening time. In booting stage, the RH % increases with different height at which the sensors installed with highest values observed during morning time ranged from 83.29 to 87.95%. Low values recorded in evening that fell between 63.94 to 31.48% ranges. The RH% values observed in flowering stage during morning and night time were almost close to each

other while the highest % ranged from 89.02 to 87.71 recorded in morning at 0.5m and 8 m respectively.

At grain filling stage, the night and morning RH% values follows close pattern which decrease slightly upto afterwards it increases. In this stage noon and evening relative humidity also followed a same pattern with an abrupt rise in RH at height of 0.5m (77.24% in noon and 71.96% in evening) while with further increase in height RH values were almost same with value of 27.88 and 23.93% at 8m in noon and evening respectively. The morning recorded the highest RH% values amongst them with a range of 80.59 to 73.89%. On the other hand lowest RH% values of range observed during evening. In milking RH values at 0.5m doesn't changes much diurnally so graph clustered at 0.5m height 77.72, 73.03, 75.452 and 77.41% during morning, noon, evening and night. The lowest RH values were recorded during noon and highest in the morning. In this stage during whole diurnal period sensor RH profile showed similar pattern of abrupt increase at 0.5m and lower values with increasing height. During dough stage the RH % profile of noon and evening showed an abrupt increase at height of 0.5m. The RH values were lowest in noon ranging from 81.49 to 57.02% while it was highest for morning.

4.6 Diurnal trend of Energy balance

4.6.1. Maize crop

4.6.1.1 At sowing

The different components of energy balance like net radiation, latent heat flux, sensible heat flux and ground heat flux are shown in Fig. 4.15. The crop sown on 19th July, 2017. In this stage the soil surface was dry and didn't have any cover and it was exposed to solar radiation thus the soil crust was dry. H, G and LE followed exactly the same trend of Rn. The maximum Rn and were 468.8 W m⁻², 353.3 W m⁻² at 13.30 hrs. There was a time lag to reach the maxima in case of H and G. The maximum H was 119.1 W m⁻² at 14:30 hrs and G was 34.6 W m⁻² at 15:30 hrs, respectively. The partitioning of maximum Rn (at 13:30 hrs) of different components like LE, H and G were in decreasing trend of 75.5%, 23.4% and 1.1%. As soil was dry, the sensible heat flux was away from the surface whole day which indicates soil surface is the source of sensible heat generation. The soil evaporation contributes towards latent heat flux as

there was no crop canopy to transpire. So moisture loss from the bare soil is the only source of LE.

The air temperature was low during morning and varied between 27.3 to 33.3 °C. The air temperature was increasing upto 15:30 hrs and after that it decreased. The vapour pressure was more in morning and decreased after that. Wind speed (ms^{-1}) varied from 0.05 to 3.5. There was no pattern of wind speed. Bowen ratio varied from 0.16 to 0.31.

4.6.1.2 Four (4) leaf Stage

The energy balance components at 4 leaf stage (10 DAS) was given in Fig. 4.16. It was a clear sunny day but the crop canopy was less so soil crust was dry. The R_n and LE were reached the maxima at 13:30 hrs and the values were 492.16 W m^{-2} and 329.2 W m^{-2} , respectively. The sensible heat flux (111.0 W m^{-2}) and soil heat flux (72.3 W m^{-2}) reached a peak at 14:30 hrs and declined thereafter. There was always a time lag observed between the maxima of R_n and H & G . The higher contribution of H is mainly due to less crop cover (low LAI). Contribution of evaporation from soil is dominant over plant transpiration, which contributes more to LE.

The maize crop canopy got warmer after 15:00 hrs thus the canopy get hotter. Some amount of water from canopy in the form of transpiration keeps the leaf cooler. The air temperature recorded by the upper sensor was higher than lower sensor. Throughout the day temperature gradient was positive. There was a continuous increase of wind speed after 13:30 hrs. There may be possibility of “sensible heat advection” in the afternoon. The H varied from 1.2 to 111.0 W m^{-2} . The Bowen ratio varied from 0.16 to 0.52.

4.6.1.3 Six (6) leaf Stage

Six leaf stage in maize crop occurred in 30 DAS (18th August, 2017). Data presented in Fig. 4.17. The day was a clear sunny day. The R_n reached peak (548.48 W m^{-2}) at 13:30 hrs. The LE followed the same pattern of R_n and the highest values was 424.791 W m^{-2} . The peak of sensible heat flux reached early at 12:30 hrs and the highest value was 69.12 W m^{-2} . In case of G , a time lag observed and reached its highest (85.77 W m^{-2}) at 15:30 hrs. The partitioning of R_n in LE, H and G were 77.49%, 11.03% and 11.52%, respectively at 13.30 hrs.

4.6.1.4 Knee high stage

This is one of the important phenological stage in maize. This stage of maize was occurred on 38 DAS (27th August, 2017). The day was clear and sunny and irrigation was given on 23rd August, 2017. The energy balance components are presented in Fig. 4.18.

The LE followed the same pattern of Rn. The maxima of Rn and LE was at 12:30 hrs and the values were 570.2 and 438.1 W m⁻², respectively. The partitioning of net radiation (Rn) into its different components at 12:30 hrs was 76.8% for LE, 18.8% for H and 4.7% for G. the highest H value was observed at 13:30 hrs and the value was 438.1 W m⁻². The peak value of soil heat flux reached at 14:30 hrs and the value was 50.9 W m⁻². As soil moisture was abundant the LE was more compare to H and G. That is the reason that the generation of sensible heat from surface was lower.

The air temperature was higher (around 32.9°C) when the canopy temperature was lower as transpiration was more. The value of H changed from 2.54 to 106.13 W m⁻². The vapour pressure increased after 14:30 hrs but the vapour pressure gradient at the same time started decreasing. At this stage the LAI was around 2.40 and plant height was 240 cm. The soil surface was moist as irrigation was given 3 days earlier. The temperature gradient was sufficiently high to increase LE. The surface roughness was a bit high due to crop height. The Bowen ratio varied from 0.04 to 1.5.

4.6.1.5 Tasseling stage

At this stage the Rn varied from 15.97 to 533.76 W m⁻² (Fig. 4.19). The peak of Rn reached at 13:30 hrs and the value was 533.76 W m⁻². The soil heat flux varied from 0.98 W m⁻² to 37.45 W m⁻² and the peak value reached at 15:30 hrs. The H varied from 4.68 to 393.00 W m⁻² and the peak value was attained at 13:30 hrs. Due to some cloud around 12:30 to 13:30 hrs, some variation was there in the pattern of H. the cloudiness altered the trend of H and G a little bit. The crop was not having any water stress. The soil heat flux also follow the same pattern of Rn.

The sensible heat flux (H) was positive throughout the day, but there was no advection. In the afternoon the temperature gradient increased as air mass passing over the crop canopy was warm but the canopy was cool due to transpiration. The crop surface based inversion condition was developed as availability of large evaporating

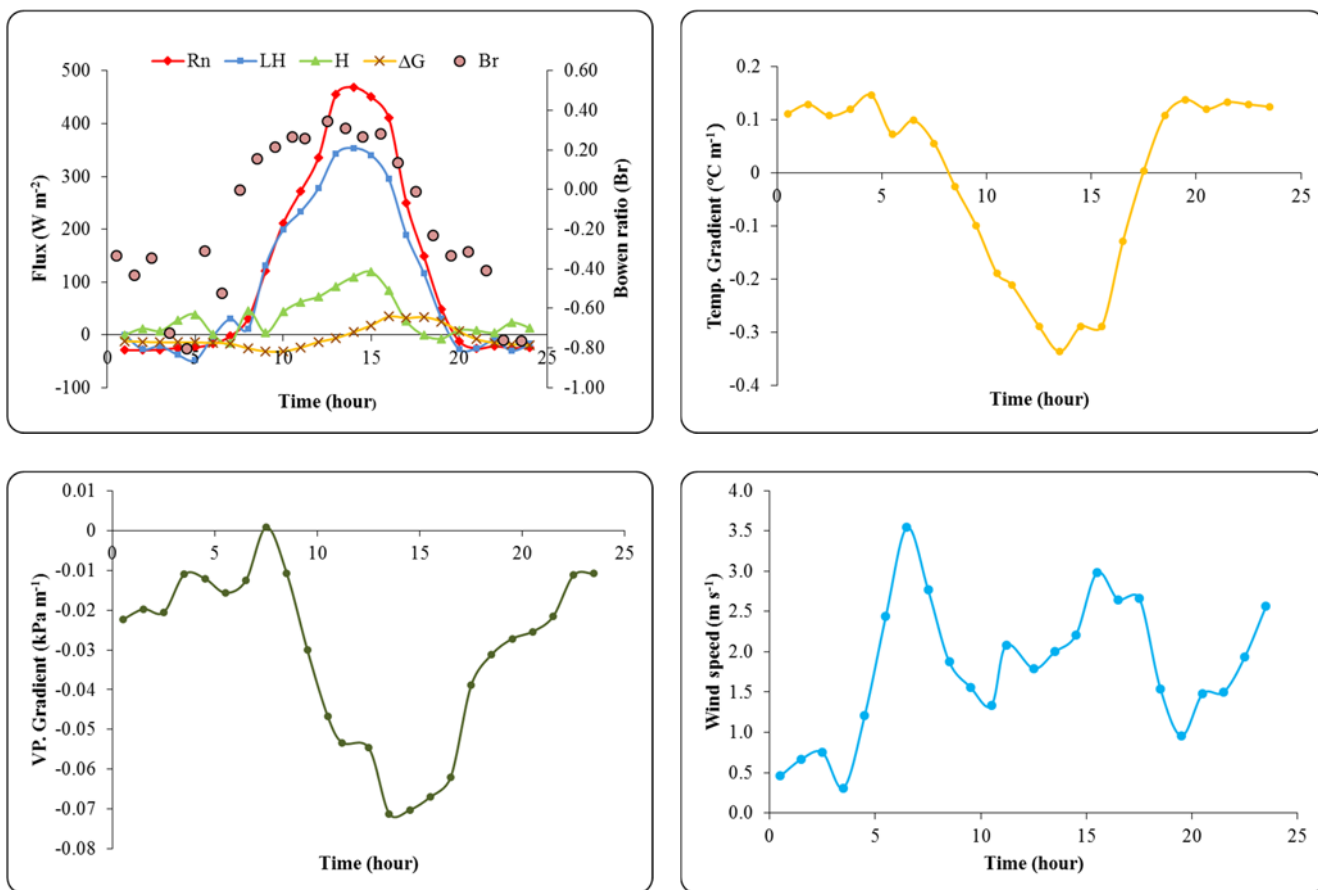


Fig 4.15 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 0 DAS (at sowing) over maize crop during *kharif*, 2017

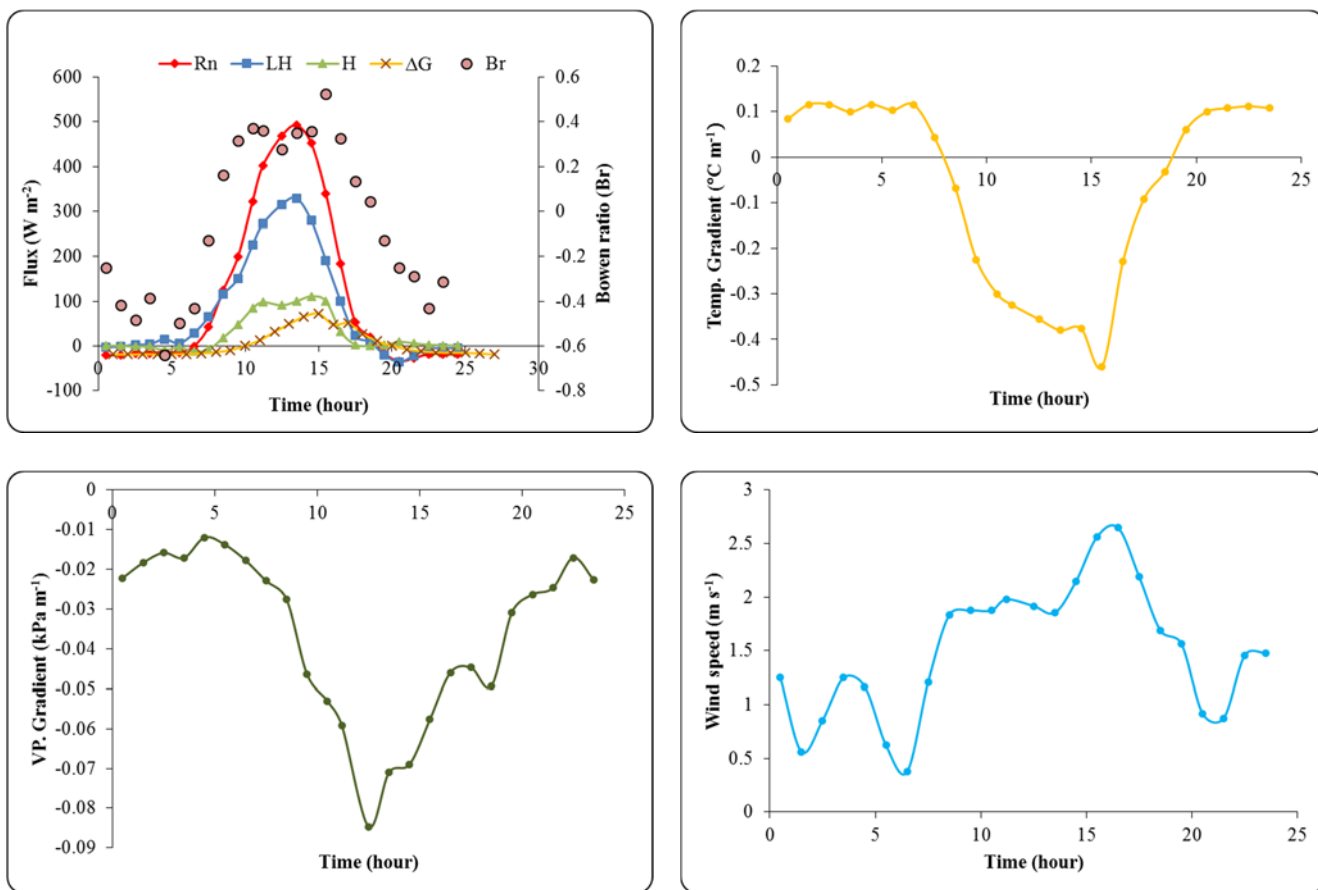


Fig 4.16 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 11 DAS (4 leaf stage) over maize crop during *kharif*, 2017

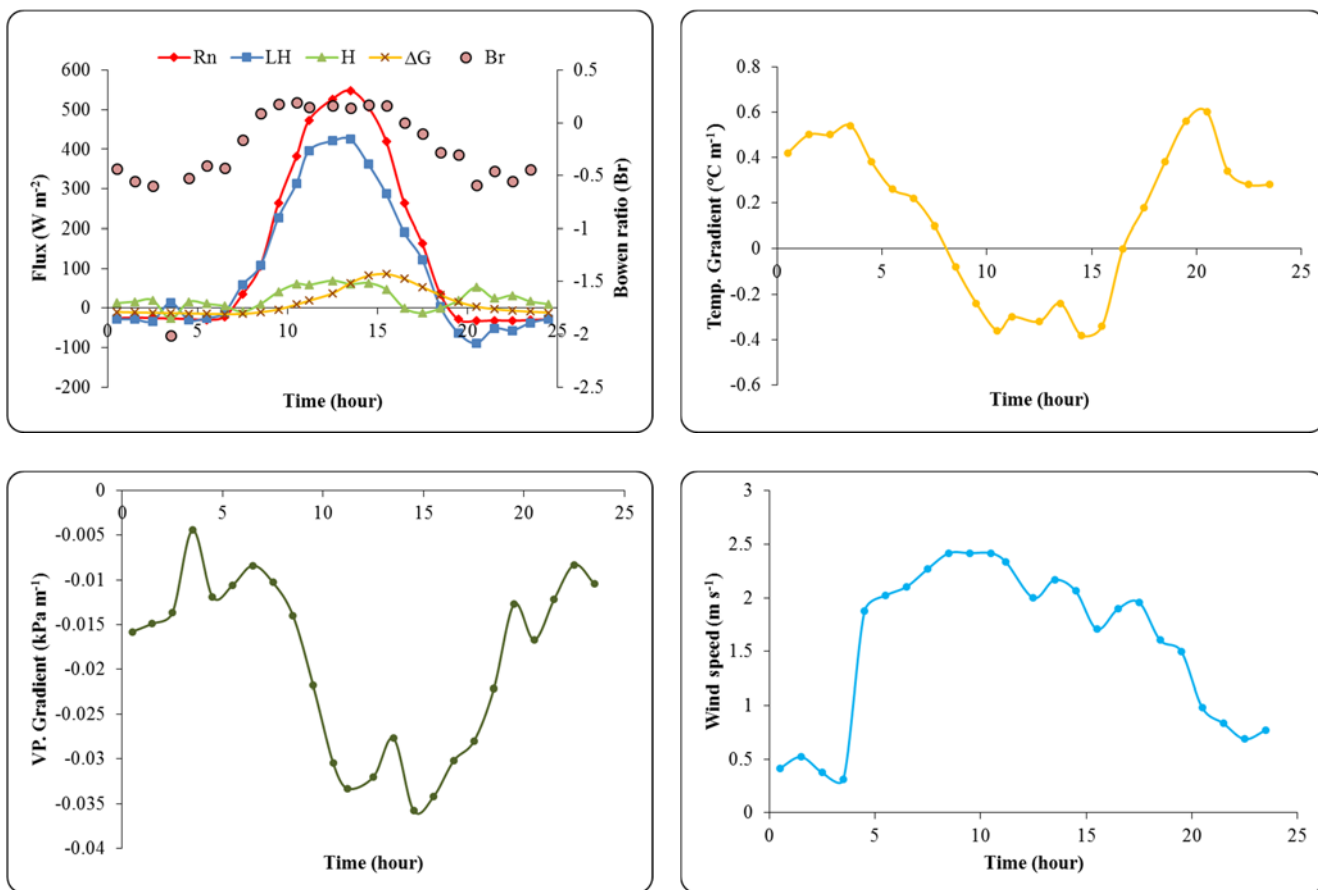


Fig 4.17 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 30 DAS (6 leaf stage) over maize crop during *kharif*, 2017

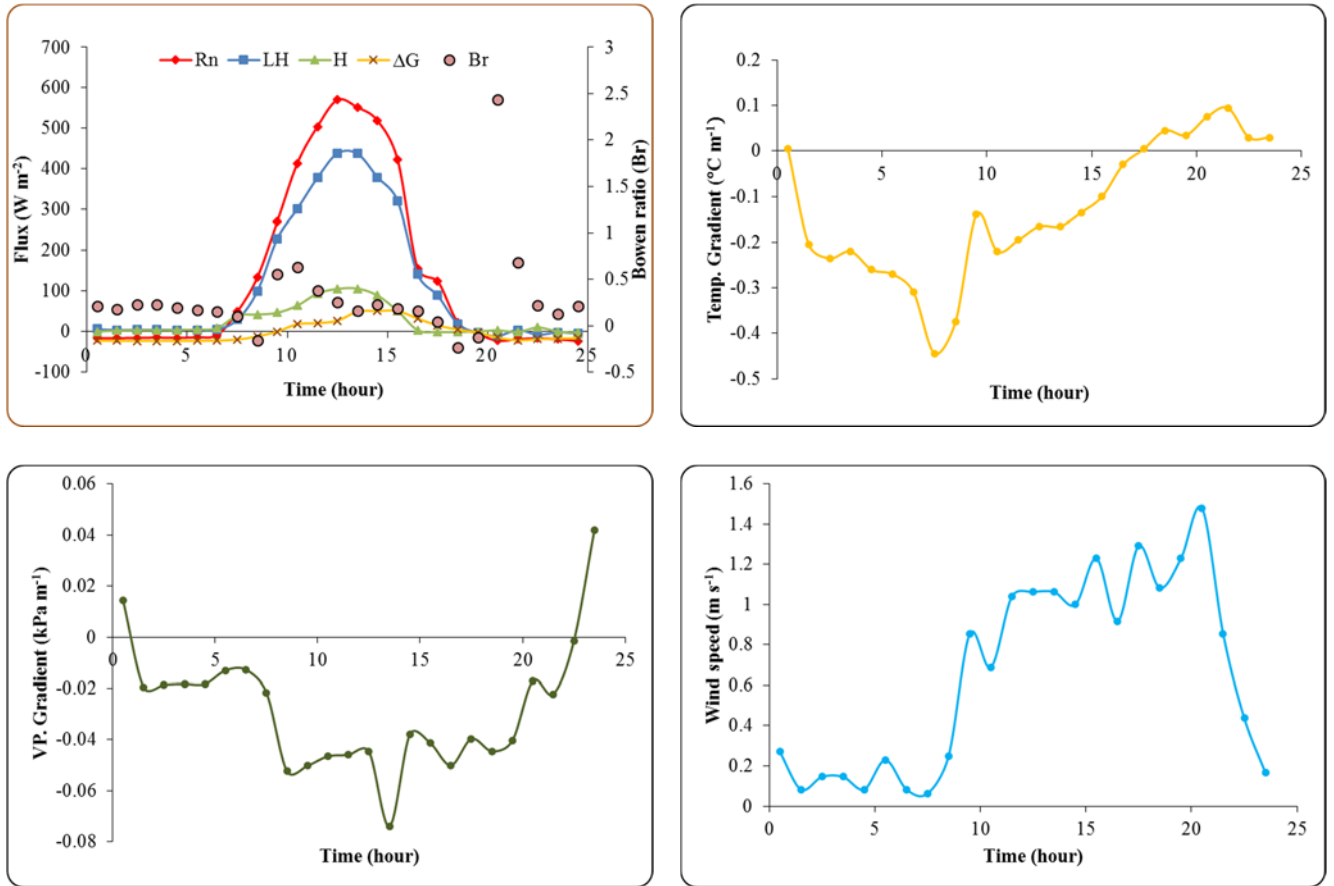


Fig 4.18 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 39 DAS (knee high stage) over maize crop during *kharif*, 2017

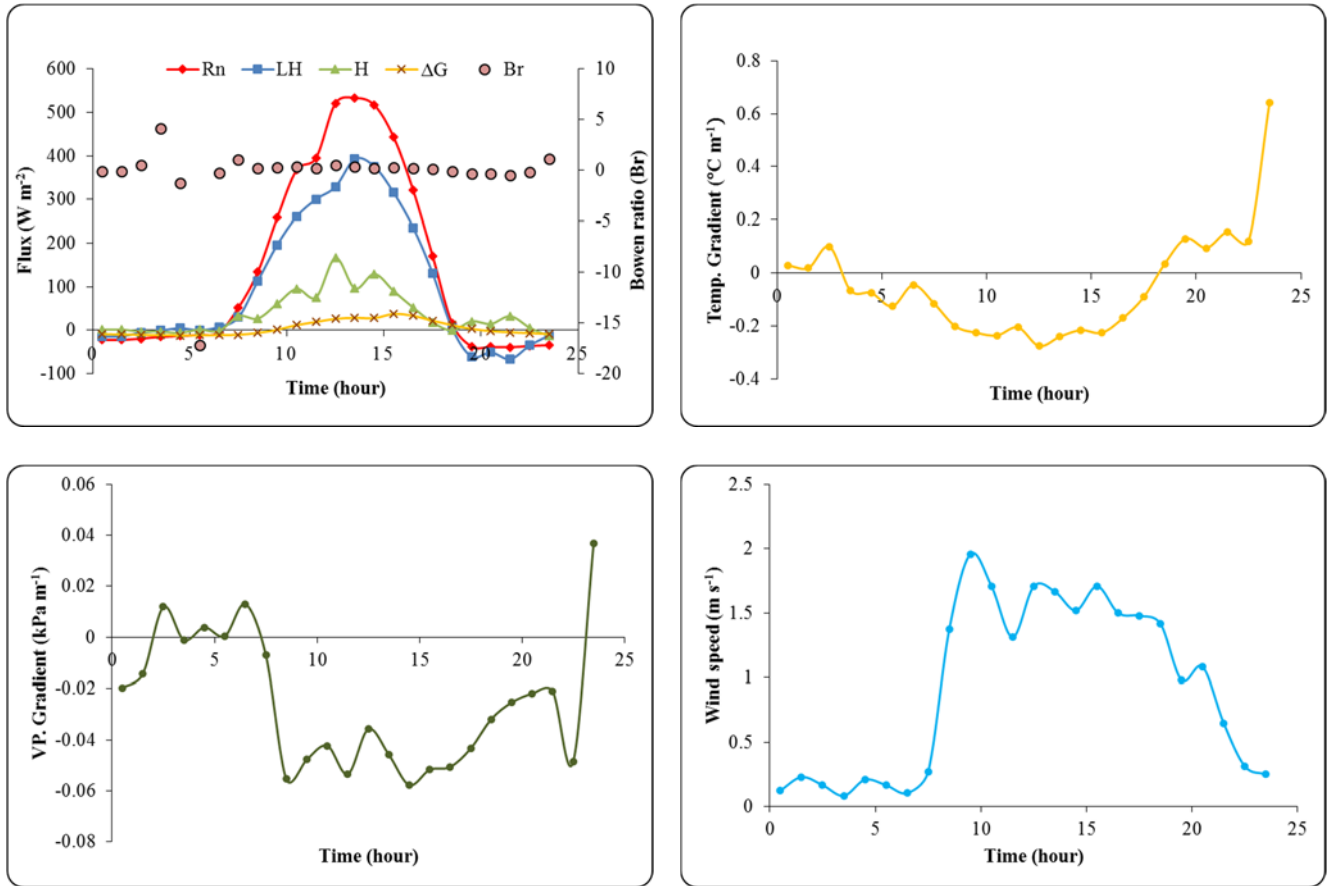


Fig 4.19 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 51 DAS (tasselling stage) over maize crop during *kharif*, 2017

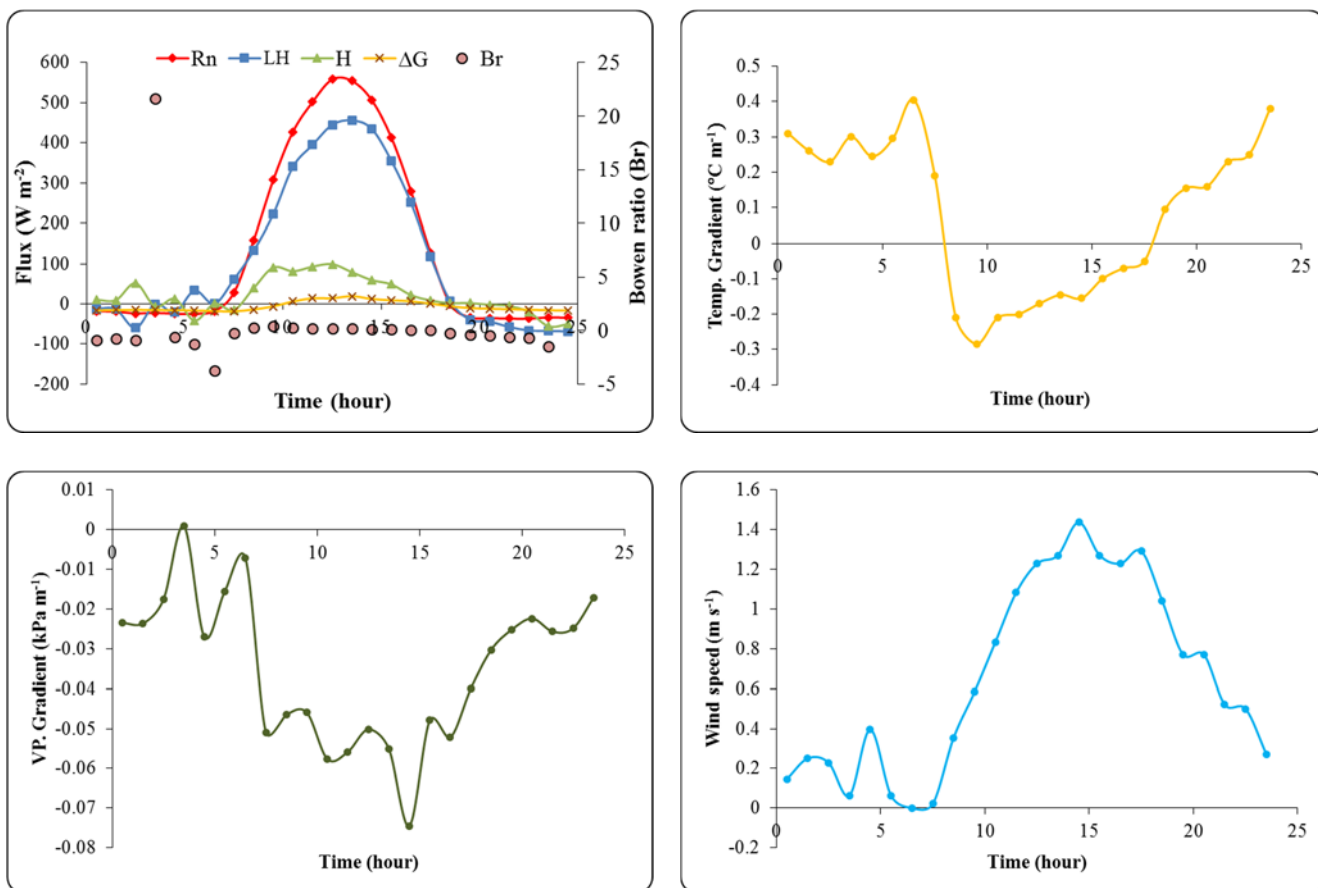


Fig 4.20 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 58 DAS (silking stage) over maize crop during *kharif*, 2017

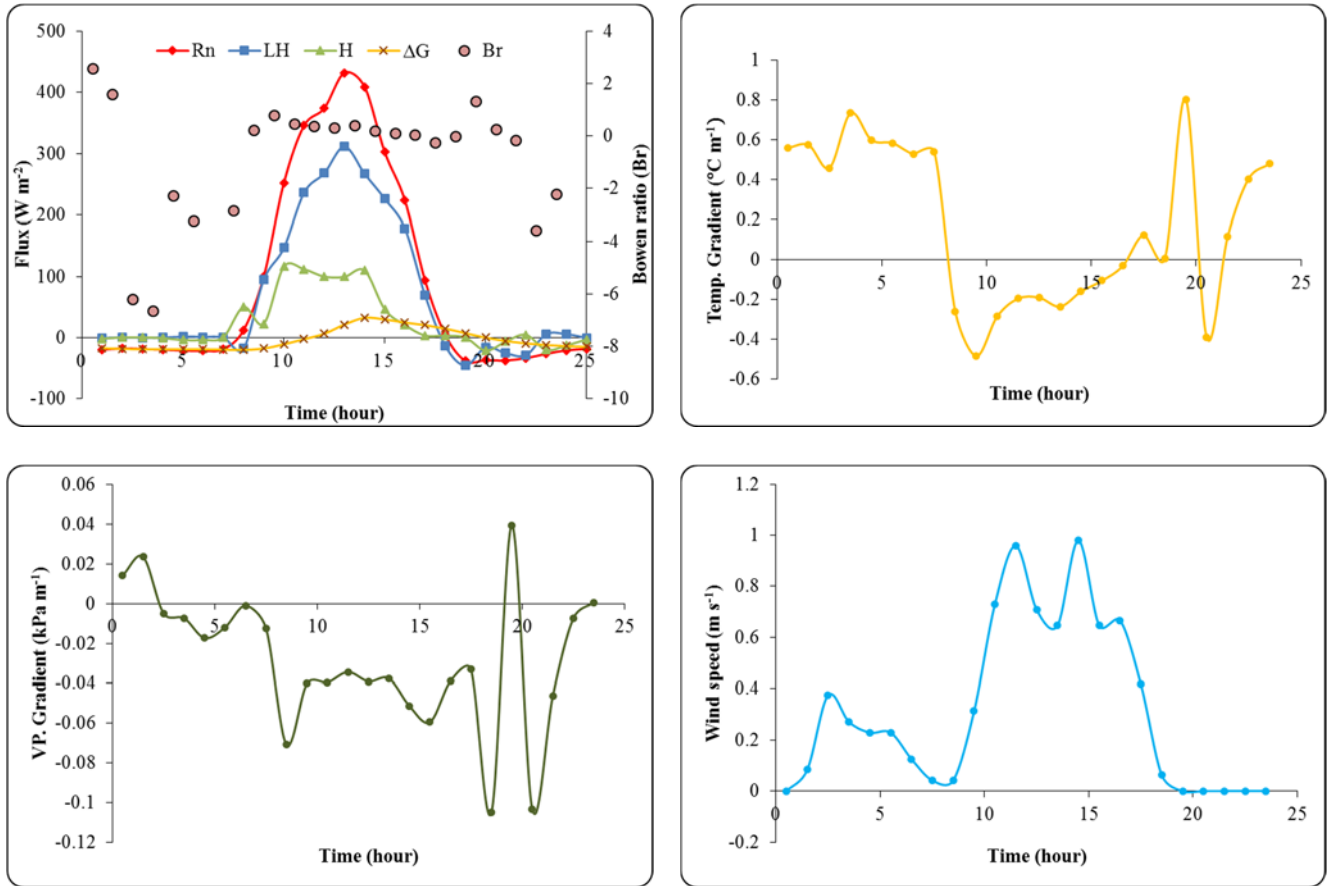


Fig 4.21 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 89 DAS (dough stage) over maize crop during *kharif*, 2017

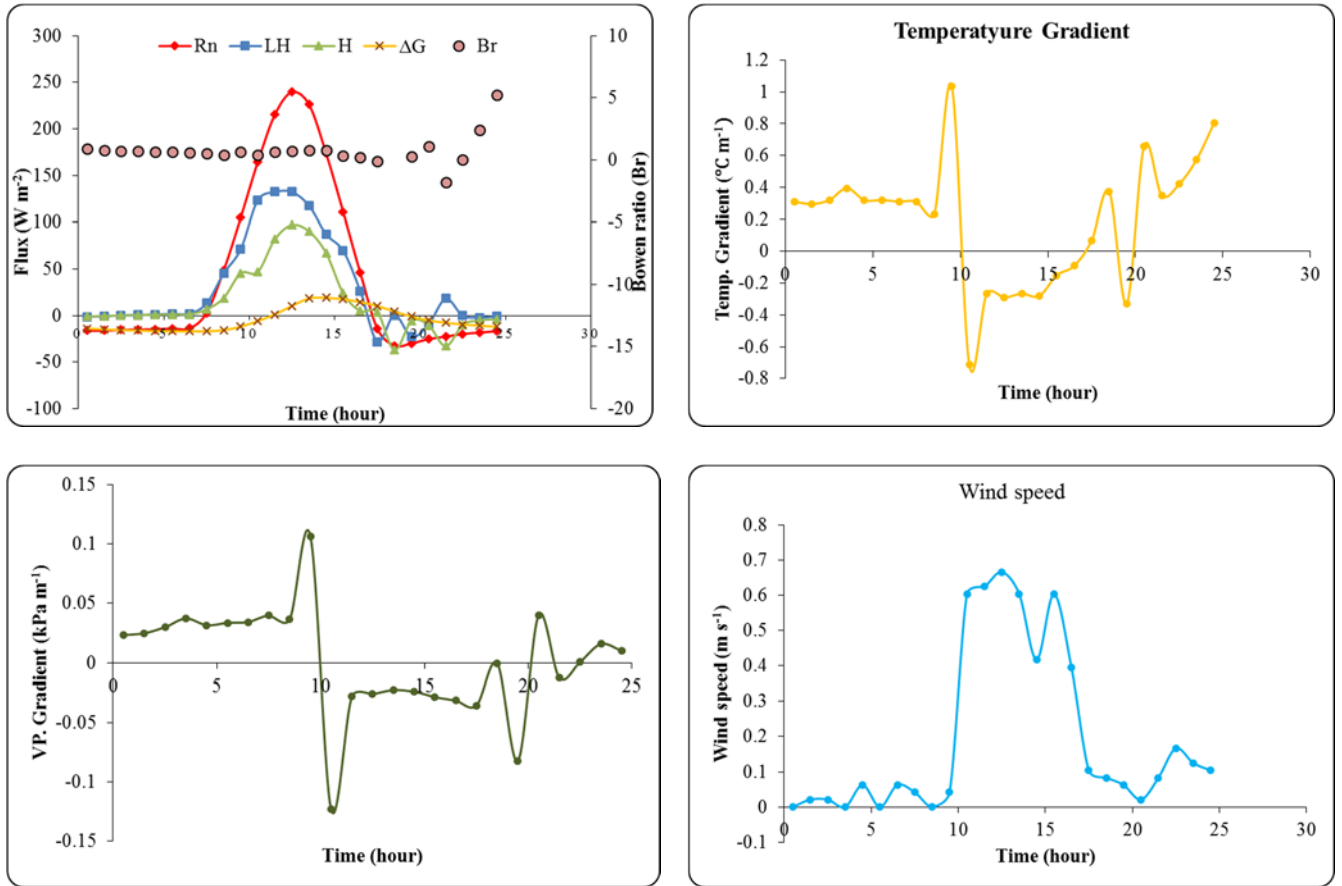


Fig 4.22 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 89 DAS (physiological maturity stage) over maize crop during *kharif*, 2017

surface and increased mixing due to higher LAI and higher plant height. Thus maximum R_n was used in LE component while G decreased due to less soil surface exposure.

4.6.1.6 Silking stage

At this stage the crop was reached a height of 1.56m and the LAI reached around 4.0. Silking stage occurred around 15th September, 2017. The R_n varied from 27.88 to 558.08 $W\ m^{-2}$ and the peak value reached at 12:30 hrs. (Fig. 4.20). The LE varied from 6.89 to 455.94 $W\ m^{-2}$ and the peak value recorded at 13:30 hrs. Sensible heat flux varied from 2.01 to 99.07 $W\ m^{-2}$ and the maxima occurred at 12:30 hrs. The value of soil heat flux is low as the canopy covered the soil surface and the peak value observed at 13:30 hrs 19.33 $W\ m^{-2}$.

As the soil is having sufficient moisture the soil was wet. The portioning of R_n into LE was 82.26%, into H was 14.25% and into G was 3.49%. The higher percentage of LE indicated the presence of other source of energy. The LE value was more in the afternoon compared to morning time. The sensible heat advection was observed throughout the day. The magnitude of advection increased in the afternoon thus the LE values increased over net radiation. This is evident from temperature and vapour pressure gradient. Similar type of results was also observed by Kim (1989) and reported that in anthesis stage the values of H varied from 10 to 140 $W\ m^{-2}$ while latent heat flux peak was at 12.00 hrs.

4.6.1.7 Dough stage

The dough stage observed around 16th October, 2017 and the crop reached at 89 DAS while the LAI was around 2.60 and started decreasing and the crop height was 2m. The energy balance components are depicted in Fig. 4.21. The R_n varied from 4.63 to 408.96 $W\ m^{-2}$. The LE ranged from 5.57 to 267.74 $W\ m^{-2}$. The soil heat flux varied from -19.57 to 32.38 $W\ m^{-2}$.

All the energy balance components were follow the trend of net radiation. The portioning of R_n into LE, H and G were 83%, 14% and 3%, respectively. In this stage the cobs are formed and LAI also decreasing. So cobs are intercepted most of the incident radiation. That resulted shading of soil surface and ultimately reduces the soil heat flux.

4.6.1.8 Physiological maturity

The day of observation was 104 DAS (31st October, 2017) and the crop was ready to harvest. The moisture content of the grain was less considerably and crop was dried up completely. The soil moisture is also less and soil surface was dry.

The energy balance components followed the same trend of net radiation and data are presented in Fig. 4.22. The soil heat flux in this stage increased due to penetration of radiation upto the soil surface. The maximum R_n was 226.24 W m^{-2} at 13:30 hrs and it's partitioning into LE, H and G was 50%, 38% and 12%, respectively. The sensible heat flux increased as LAI was 1.42 and the crop was dry. The canopy dissipated more heat in the form of sensible heat and contributed around 40% during day time. The latent heat flux was recorded even in a dry condition of crop. It contributed more than 50% during day time. The sources for LE would have been the drying of crop and evaporation from the deeper layer of the soil profile as some cracks was developed on the soil surface. The temperature as well as vapor pressure gradient both remain negative thus giving a positive Bowen ratio. The Bowen ratio was sometimes more than 1. Even though the day time temperature were less than 35°C , the sensible heat advection was not much noticed as the crop had dried up to a great extent and contributed towards sensible heat flux.

4.6.2. Wheat crop

4.6.2.1 At germination

Various energy balance components like R_n , LE, H and G on the 8 DAS are presented in Fig. 4.23. At this stage crop was 5 cm in height, soil surface was dry as the surface was exposed to sun light. LE, H and G followed the same trend as R_n . The maximum net radiation (R_n) were 225.24 W m^{-2} at 13.30 hrs. LE and H were 162.80 W m^{-2} and 41.64 W m^{-2} at 13:30 hrs respectively.

The peak of soil heat flux (G) reached at 14:30 hrs and the value was 41.15 W m^{-2} . There was a time lag to reach peak value with R_n . The partitioning of energy into LE, H and G at time of maximum R_n (13:30 hrs) was in decreasing order of 70.7%, 18.5% and 10.8%, respectively.

The air temperature was low in the early morning and recorded a minimum 6.66°C at 5.30 hrs. After that the temperature was rising and reached maximum at 24.47°C at 14:30 hrs and decreased after that. The vapour pressure was more in the

early morning and decreased after sunrise. The Bowen ratio varied from 0.1 to 4.50 during day time. It gives error during night, sunrise and sunset time.

4.6.2.2 Crown Root Initiation (CRI) stage

The energy balance components at CRI stage were recorded at 23 DAS and are presented in Fig. 4.24. The day was clear sunny day. Soil was wet as irrigation was given 3 days back. The height of the crop was 15 cm and the average LAI was 1.25. The recorded throughout the day and night. The Rn fluxes followed the same trend and reached peak at around 13:30 hrs. The highest value of Rn recorded was 504.96 W m^{-2} and its partitioning into LE, H and G was 82.2%, 9.7% and 4.9%, respectively. The sensible heat flux reached a peak at 13:30 hrs and the value was 48.78 W m^{-2} . The soil moisture availability also reduced the H value. The contribution G was due to lower LAI. The wind was westerly in early morning but become easterly later on and remained south to east all throughout the day. Wind speed was slightly high.

4.6.2.3 Tillering stage

Tillering stage is one of the most important stage of wheat crop as grain yield is dependent on effective number of tillers. Irrigation was applied 10 days before this crop so the soil was not much dry. The day was foggy. The energy balance components are given in Fig. 4.25.

The LE, H and G followed the same pattern of Rn. The maxima of Rn and latent heat flux (LE) was occurred at 12:30 hrs and the values were 260.28 W m^{-2} and 191.01 W m^{-2} , respectively. The peak value of H reached at 11:30 hrs and the value was 55.21 W m^{-2} . The G reached the peak value at 14:30 hrs and the value was 25.30 W m^{-2} . As the soil were moist and solar radiation was available the sensible heat production from the soil surface was low. The partitioning of Rn in different components at 12:30 hrs was 73.39% for LE, 19.22% for H and 4.80% for G.

4.6.2.4 Booting stage

Energy balance data at booting stage (90 DAS) recorded using multi-level AWS. The components of energy balance at booting stage were given in Fig. 4.26. Soil was wet as irrigation was given on 85 DAS. The sky was clear and peak Rn recorded 302.21 W m^{-2} at 12:30 hrs and maintained a normal inverted parabolic curve. The partitioning of Rn into different components like LE was 89.91%, H was 6.24% and G was 3.85%. The soil moisture contributes to higher LE portion compare to S. The sensible heat flux

(H) was at 13:30 hrs and the value was 20.61 W m^{-2} . The G was reached a maxima at 13:30 hrs and the value was 13.73 W m^{-2} .

4.6.2.5 Flowering stage

In flowering stage (98 DAS), the R_n followed an inverted parabolic curve. The peak value of R_n was observed at 13:30 hrs and the value was 336.17 W m^{-2} (Fig. 4.27). The partitioning of R_n into LE was 84.97%, H was 4.7% and G was 5.67%. Moist soil contributes more LE compare to H and G. The soil moisture availability also reduced the H value.

The contribution G was low due to higher LAI. The wind was northerly in early morning but become easterly later on and remained south-east all throughout the day. Wind speed was slightly high.

4.6.2.6 Dough stage

The energy balance components at dough stage recorded at 124 DAS are presented in Fig. 4.29. It was a clear sunny day and soil was wet with the irrigation given on 123 DAS. The height of the crop was 98 cm and the average LAI was 3.25. The data recorded throughout the day and night.

The R_n fluxes followed the same trend and reached peak at around 13:30 hrs. The highest value of R_n recorded was 504.96 W m^{-2} and its partitioning into LE, H and G was 85.67%, 5.93% and 9.25%, respectively. The sensible heat flux reached a peak at 11:30 hrs and the value was 67.96 W m^{-2} . The soil moisture availability also reduced the H value. The contribution G was lower due to lower LAI. The wind was westerly in early morning but become easterly later on and remained south to east all throughout the day. Wind speed was slightly high.

4.6.2.7 Physiological maturity

The energy balance components at physiological maturity stage are presented in Fig. 4.30. It was clear sunny day and soil was dry. The height of the crop was 98 cm and the average LAI was 1.98 due to senescence of crop. The recorded throughout the day and night. The R_n fluxes followed the same trend and reached peak at around 13:30 hrs. The highest recorded value of R_n was 328.32 W m^{-2} and it's partitioning into LE, H and G was 57.58%, 19.76% and 13.06%, respectively. The sensible heat flux reached its peak at 13:30 hrs and the value corresponding to it was 77.55 W m^{-2} . As the soil was

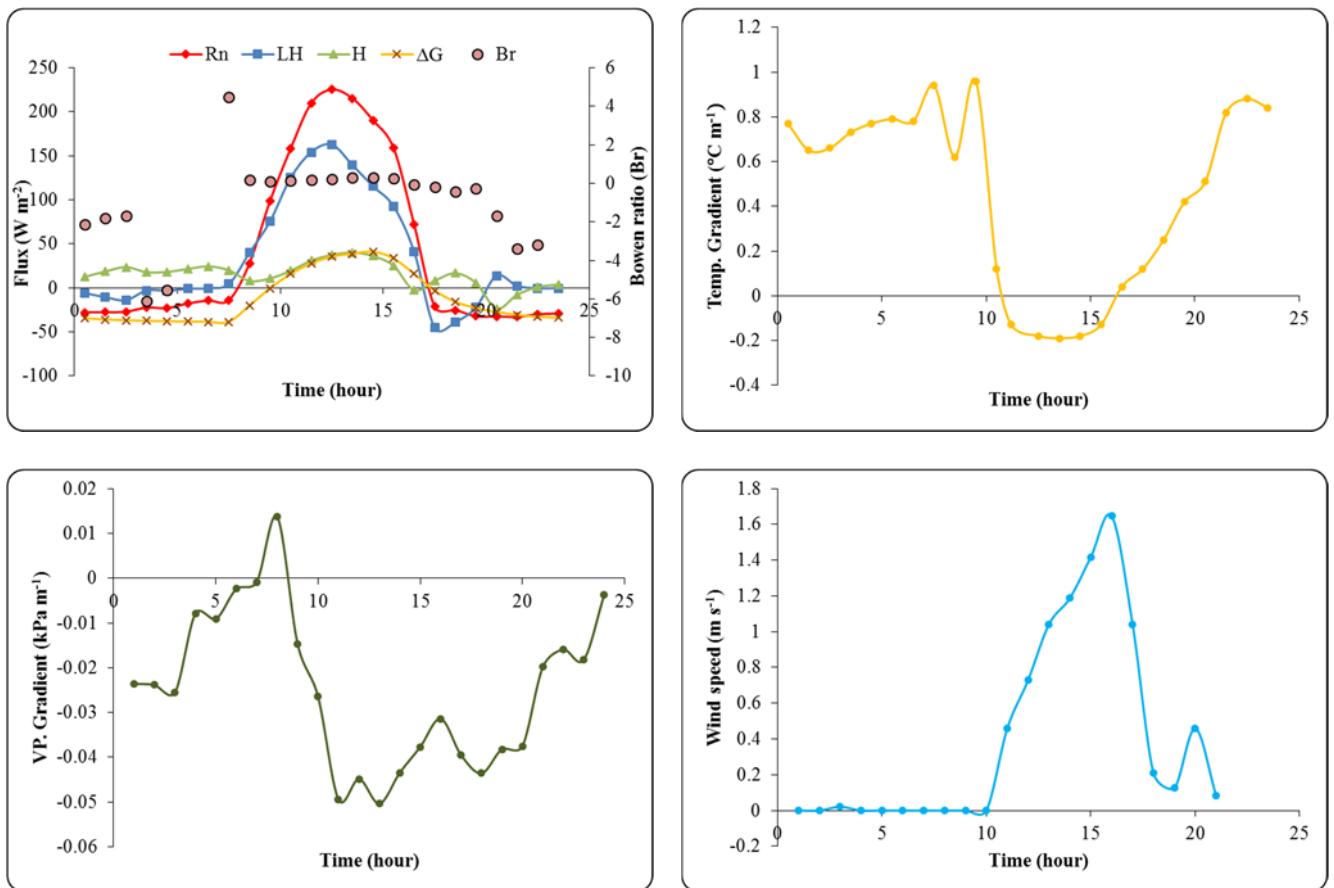


Fig 4.23 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 8 DAS (germination stage) over wheat crop during *rabi*, 2017-18

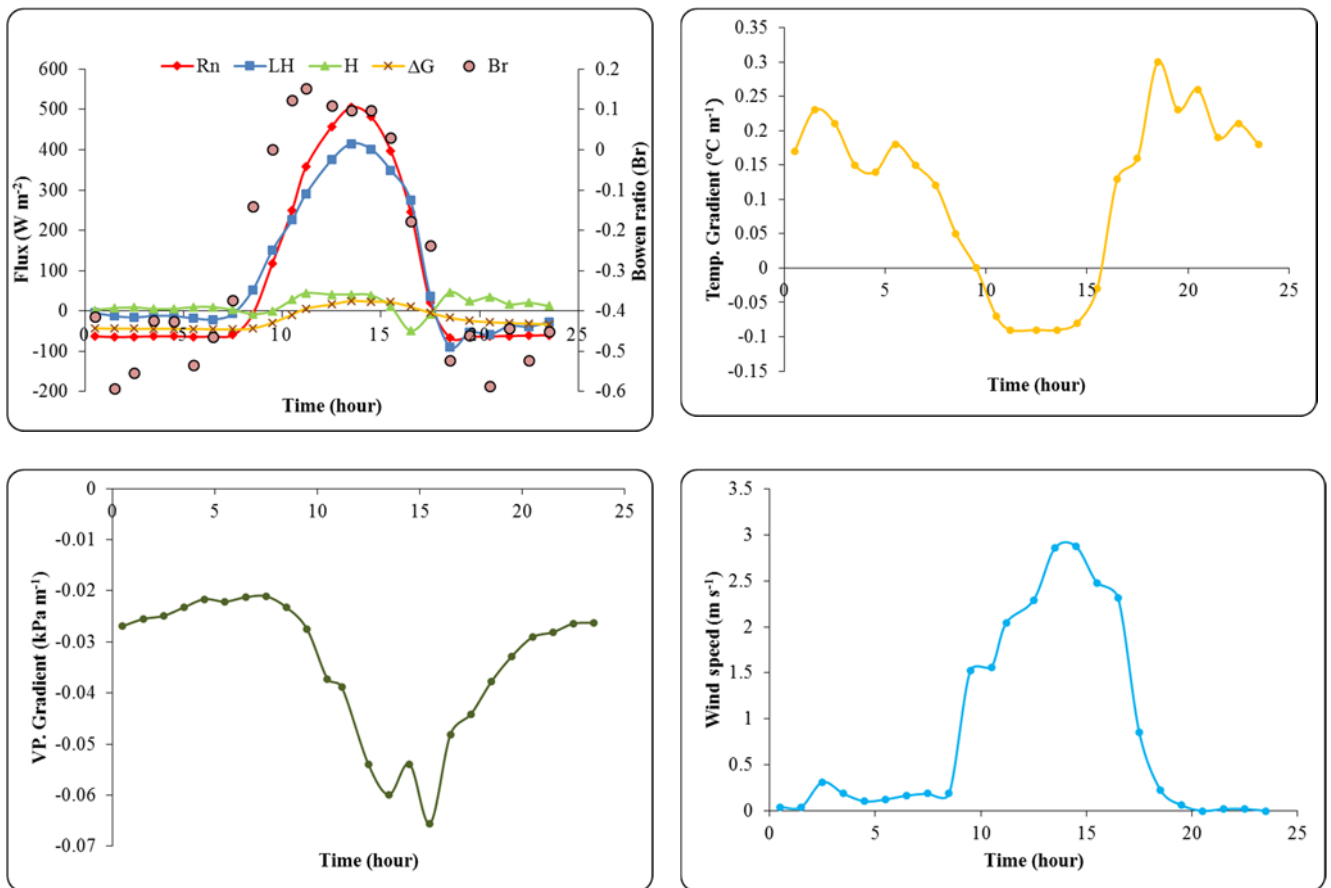


Fig 4.24 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 23 DAS (CRI stage) over wheat crop during *rabi*, 2017-18

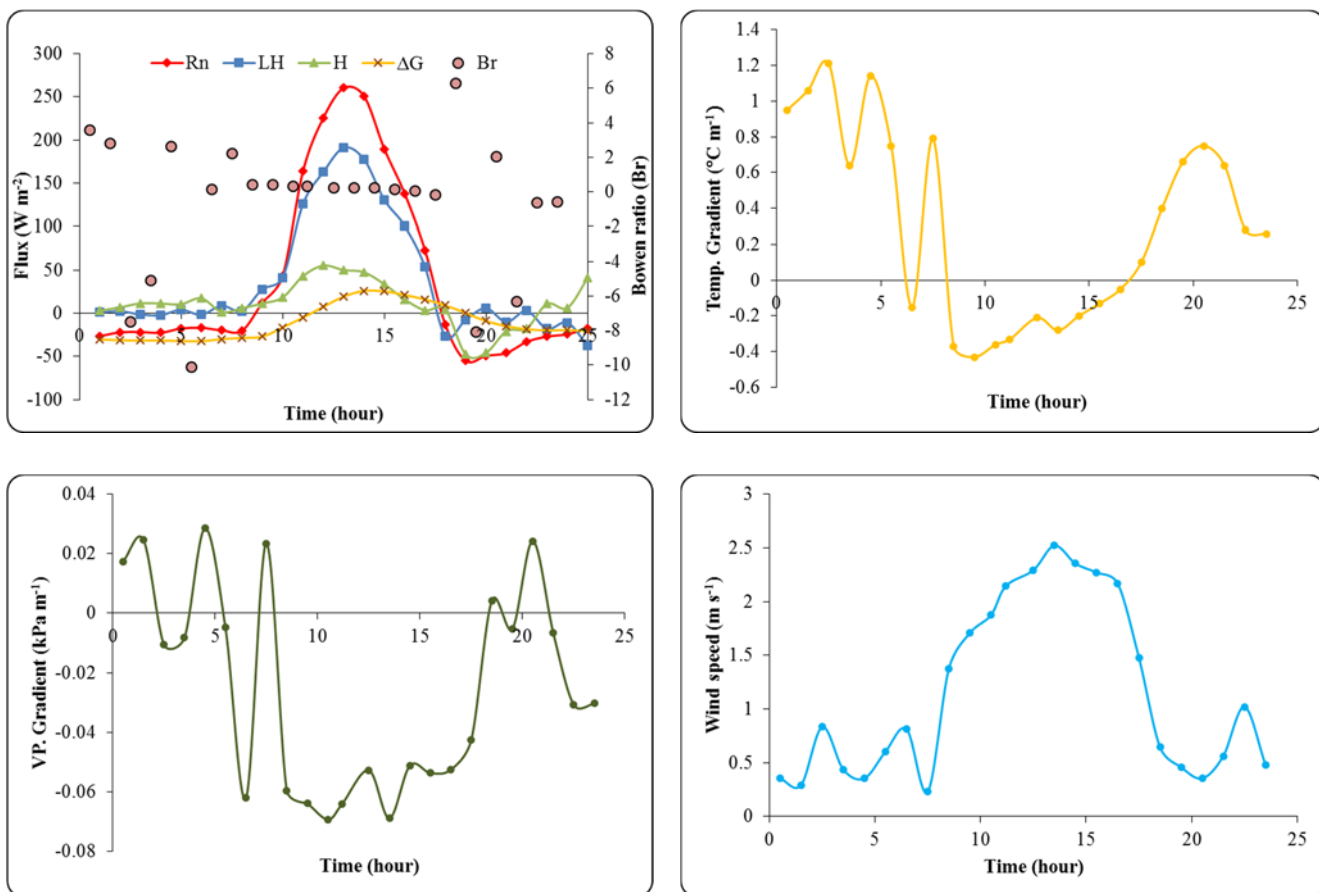


Fig 4.25 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 54 DAS (tillering stage) over wheat crop during *rabi*, 2017-18

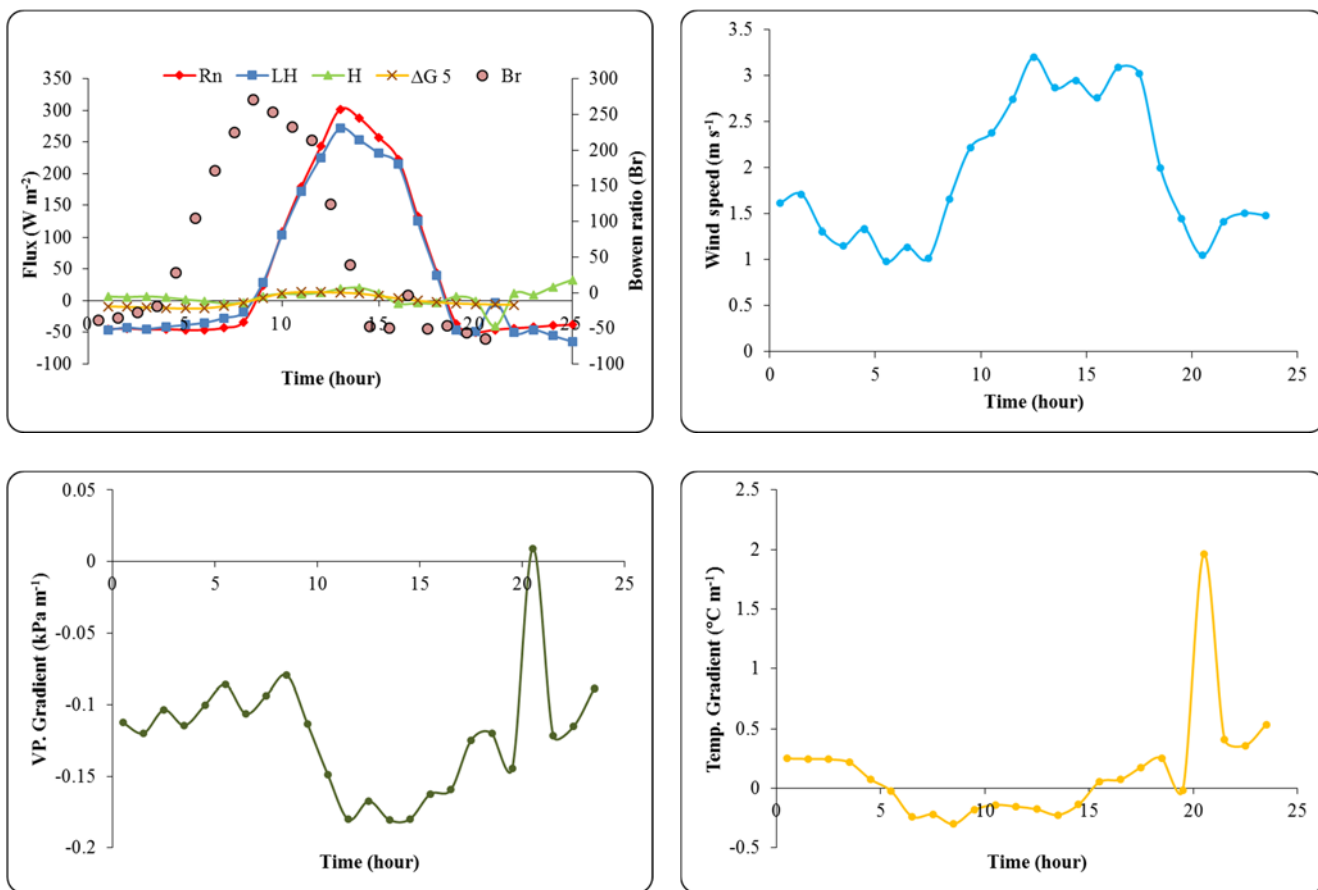


Fig 4.26 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 94 DAS (booting stage) over wheat crop during *rabi*, 2017-18

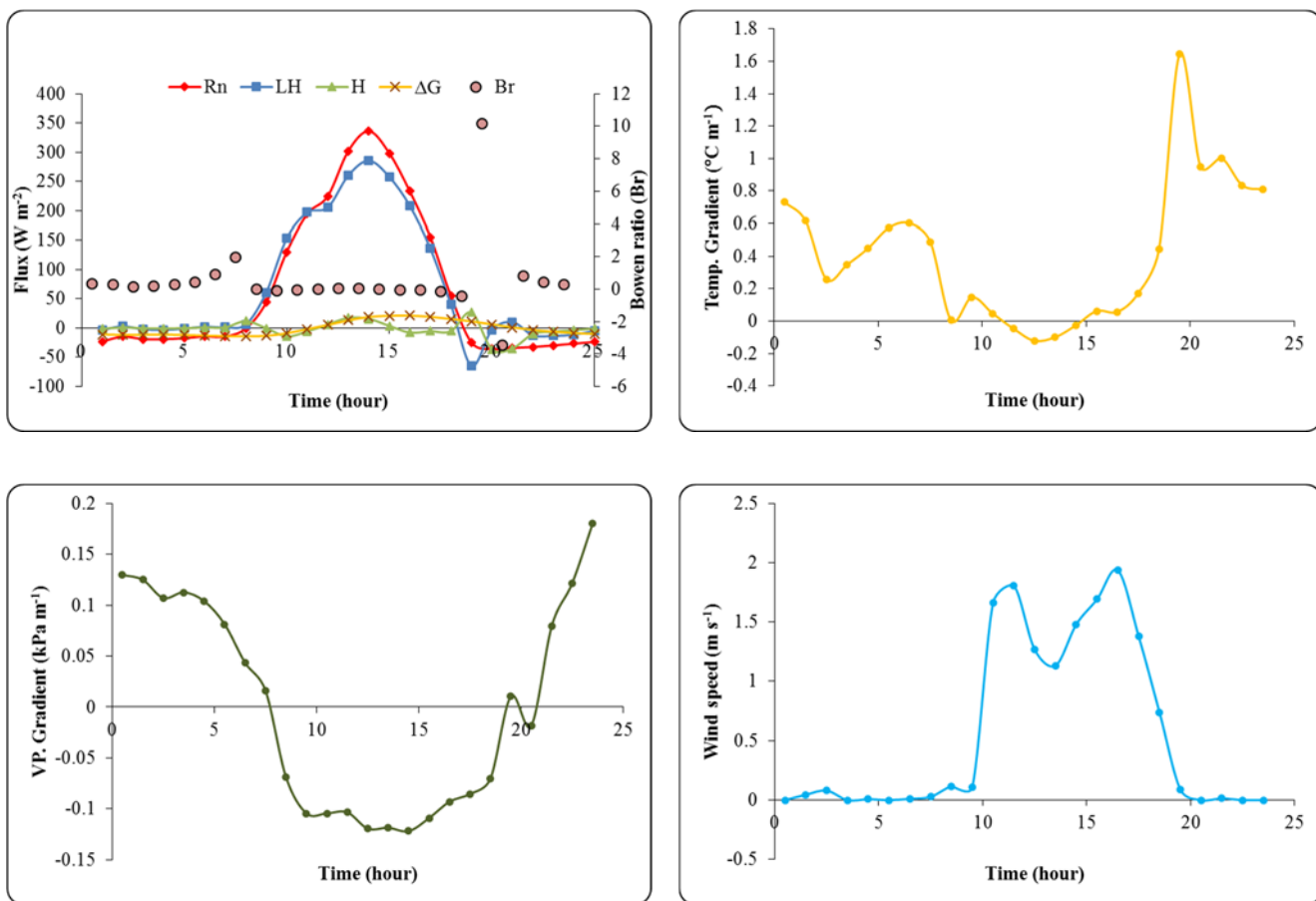


Fig 4.27 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 98 DAS (flowering stage) over wheat crop during *rabi*, 2017-18

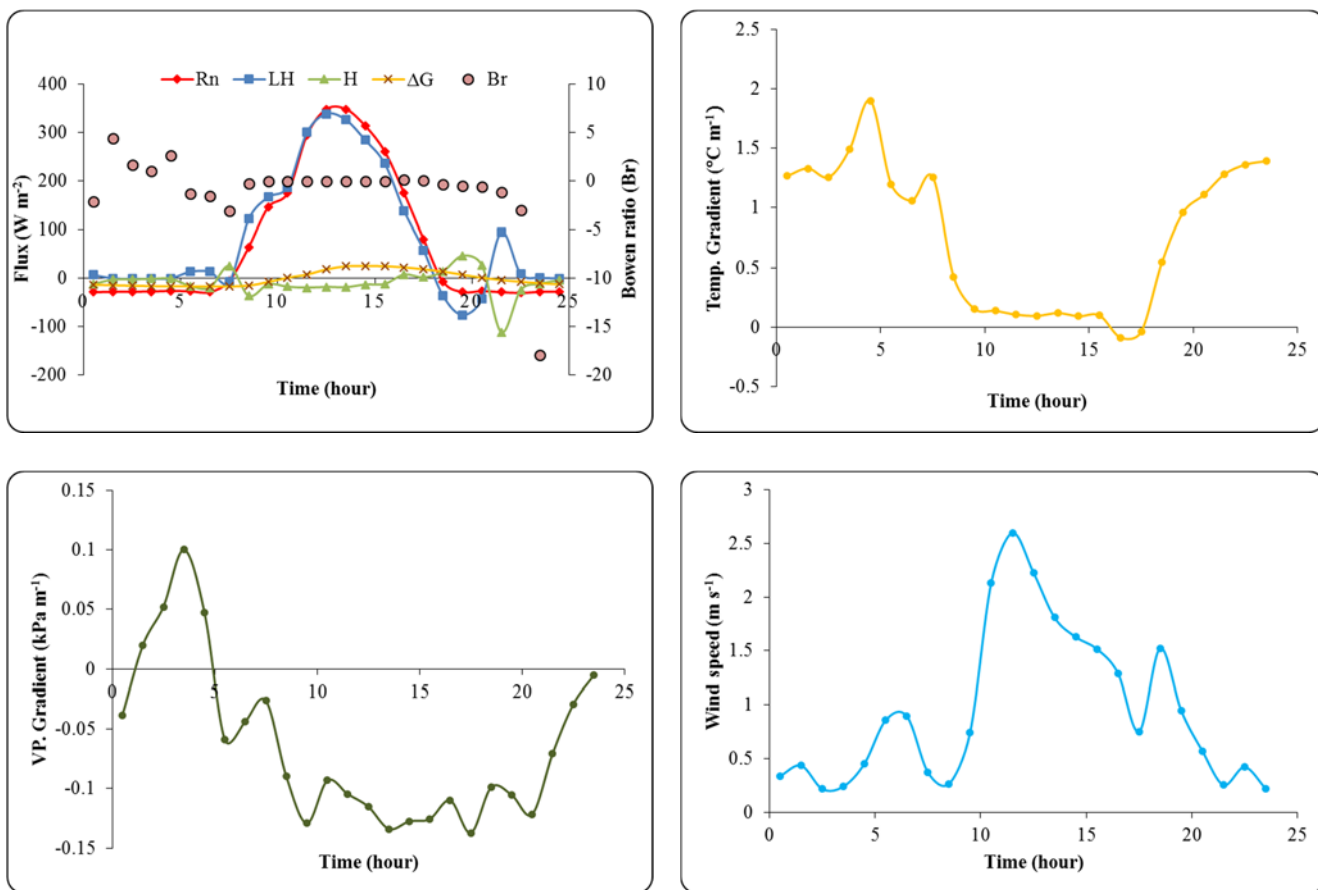


Fig 4.28 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 110 DAS (grain filling stage) over wheat crop during *rabi*, 2017-18

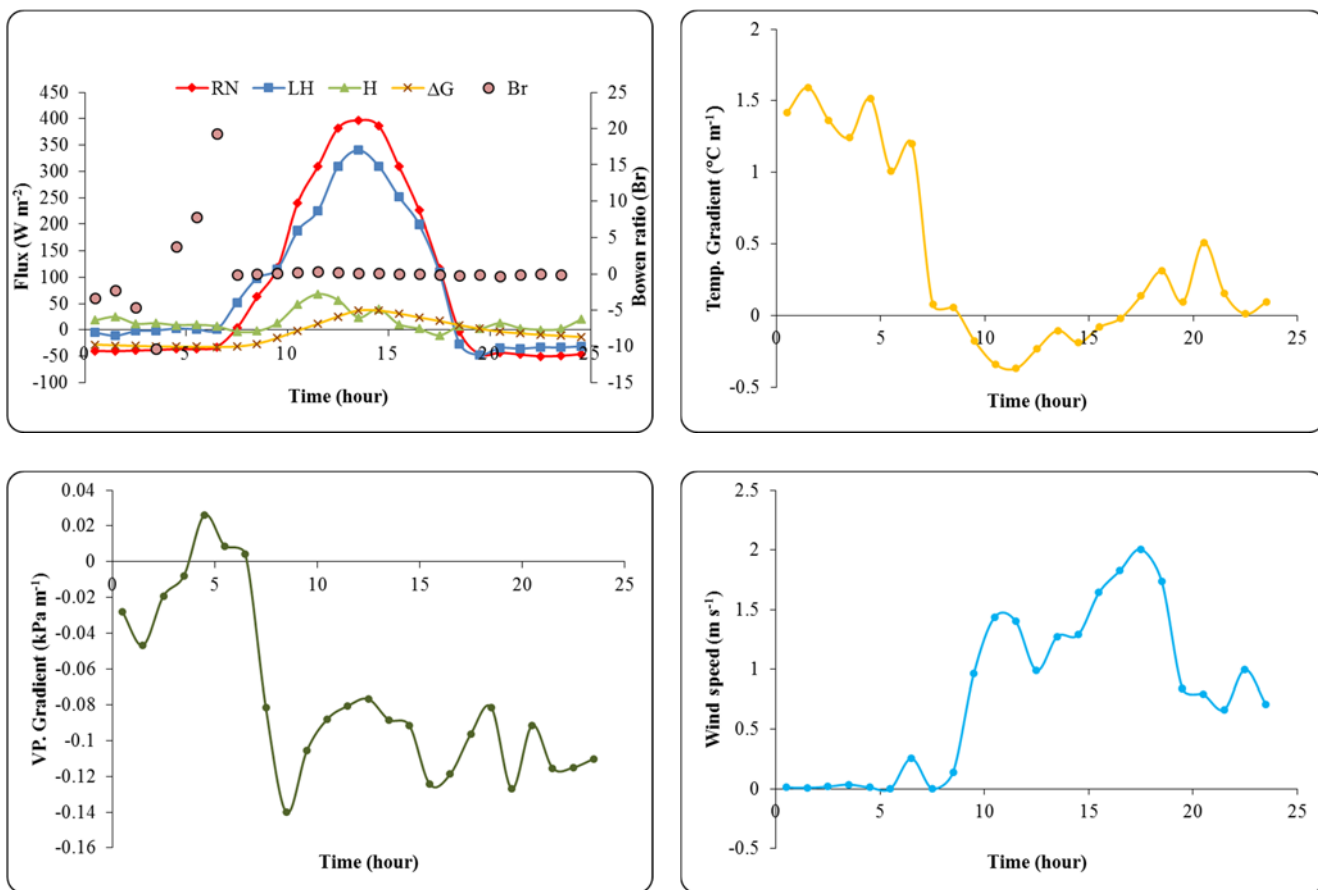


Fig 4.29 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 124 DAS (dough stage) over wheat crop during *rabi*, 2017-18

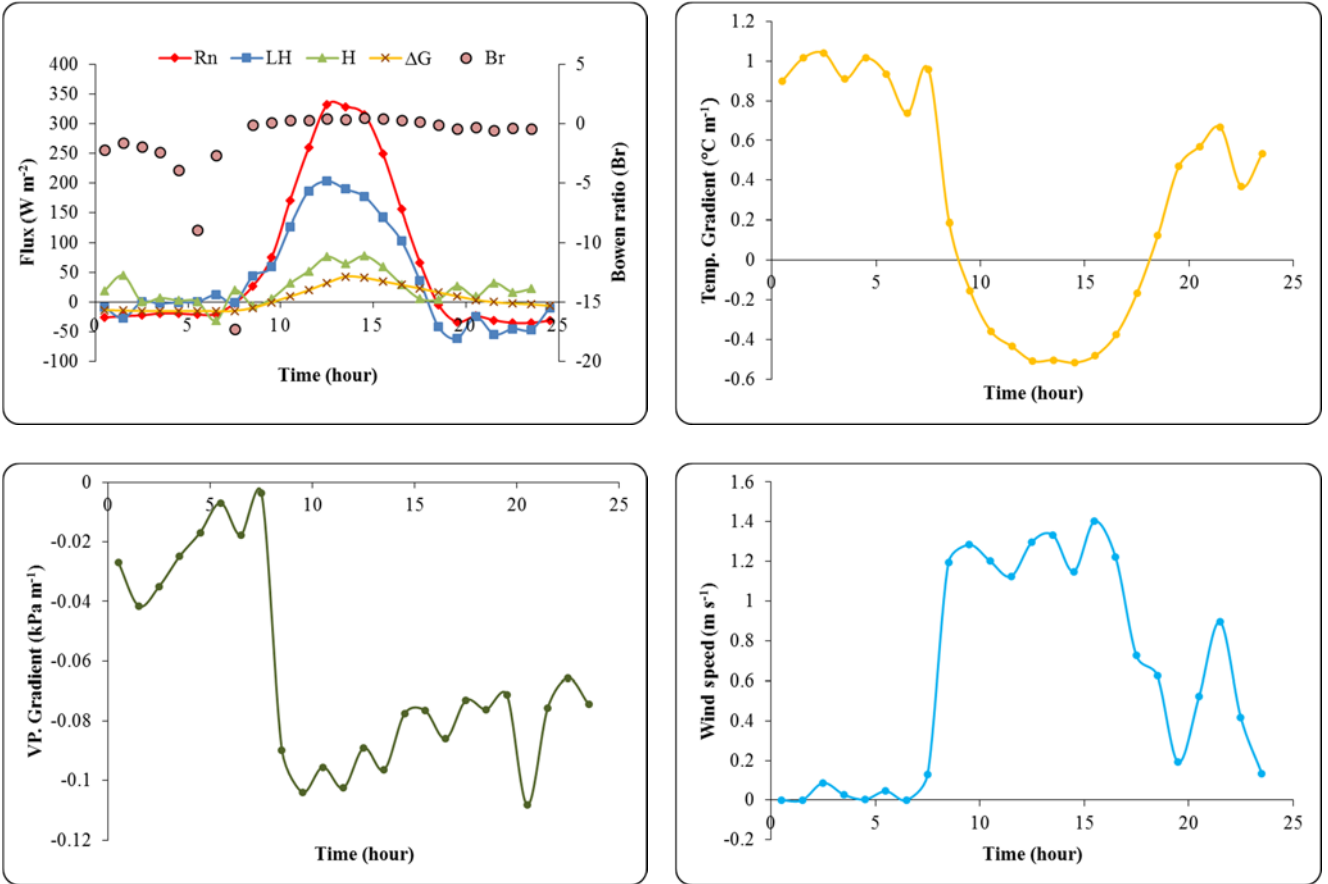


Fig 4.30 Diurnal pattern of energy flux, bowen ratio, temperature gradient, vapor pressure gradient and wind speed at 132 DAS (at physiological maturity) over wheat crop during *rabi*, 2017-18

dry at the time of maturity, the LE value reduced and more energy converted to sensible heat. The contribution G was more due to lower LAI. The wind was westerly in early morning but become easterly later on and remained south to east all throughout the day. Wind speed was slightly high.

4.7 Trend of energy balance for a cloudy day and cloud free day

4.7.1 Maize crop

At silking stage the crop was reached a height of 1.56m and the LAI reached around 4.0. Silking stage occurred around 15th September, 2017. The diurnal pattern of energy balance for cloudy day and clear day was presented in Fig.4.31 (a) and (b). All the components were varied through the day. The peak values of Rn, LE, H and G were 164.32 W m⁻², 132.87 W m⁻², 37.54 W m⁻² and 0.15 W m⁻², respectively. The LE, H followed the same trend of Rn but the trend was not consistent. Many up and down observed throughout the day. The soil heat flux (G) was very low throughout the day.

In clear day the Rn varied from 27.88 to 558.08 W m⁻² and the peak value reached at 12:30 hrs (Fig.4.29). The LE varied from 6.89 to 455.94 and the peak value recorded at 13:30 hrs. Sensible heat flux varied from 2.01 to 99.07 W m⁻² and the maxima occurred at 12:30 hrs. The value of soil heat flux is low as the canopy covered the soil surface and the peak value observed at 13:30 hrs 19.33 W m⁻².

4.7.2 Wheat crop

At flowering stage on a cloudy day the peak Rn, LE, H and G was 278.71, 281.65, 15.23 and 18.73 , respectively (Fig. 4.32 (a) and (b)). Multiple peaks were observed throughout the day. Net Radiation values was also recorded lower on cloudy day. In a clear day the Rn followed an inverted parabolic curve. The peak Rn value observed at 13:30 hrs and the value was 336.17 W m⁻². Moist soil contributes more LE compare to H and G. The soil moisture availability also reduced the H value. The contribution G was low due to higher LAI.

4.8 Seasonal trend of Energy balance

4.8.1. Maize crop

The data of seasonal energy balance shows the variation of energy balance components for *kharif*, 2017 in different phenological stages of maize crop and the data is presented in Fig. 4.33. The Rn in day time (8:00 hrs to 17:00 hrs) varied from 4.73

MJ m⁻² to 13.79 MJ m⁻² throughout the growing period of maize. The net radiation reached at peak at silking stage. The net radiation was above 13 MJ m⁻² in 6 leaf stage, knee high stage, tasselling stage and silking stage. At the maturity stage it decreased and received only 4.73 MJ m⁻². Partitioning of net radiation (Rn) in sensible heat (S) varied during entire crop growth period. Towards maturity the S increased. Partitioning of Rn to LE was high among all the other energy balance components. The partitioning towards LE was decreased towards the maturity of the crop.

4.8.2. Wheat crop

The seasonal energy balance data of wheat crop was presented in Fig. 4.34. The net radiation varied from 4.80 MJ m⁻² to 9.17 MJ m⁻² during *rabi*, 2017-18.

The partitioning of Rn to LE was more in grain filling stage (97.74%) but decreased thereafter. The partitioning of Rn to S was highest in tillering stage (21.04%) and partitioning of Rn towards G was highest (11.12%) at maturity of wheat crop.

4.9 ETc, ETo and Kc

4.9.1. Maize crop

The ETc and ETo for the various growth stages of Maize crop (*Kharif*, 2017) were calculated and presented in Table 4.15. The values of ETc at different growth stages of maize viz. Initial stages (0 to 20 DAS), Development stage (21 to 45 DAS), mid stage (46 to 85 DAS) and end stage (86 to 105 DAS) were 2.29 mm day⁻¹, 3.92 mm day⁻¹, 4.78 mm day⁻¹, and 2.08 mm day⁻¹, respectively. The values ETo was more and varied from 3.35 mm day⁻¹ (later stage: 85 to 105 DAS) to 4.98 mm day⁻¹ (initial stage: 0 to 20 DAS). At mid stage the ETo value was less (4.16 mm day⁻¹) compare to ETc (4.78 mm day⁻¹). Kc values were obtained from ETc and ETo relationship and varied from 0.46 (initial stage) to 1.15 (mid stage).

Table 4.15: Variation of ETc, ETo and Kc in maize crop (*kharif*, 2017).

Development stages	ETc (mm/day)	ETo (mm/day)	Kc
Initial stage (0-20)	2.29	4.98	0.46
Development stage (20-45)	3.92	4.36	0.90
Mid stage (45-85)	4.78	4.16	1.15
End stage (85-105)	2.08	3.35	0.62

4.9.2. Wheat crop

The ET_c, ET_o and K_c values of wheat crop (*rabi*, 2017-18) were varied among all the phenological growth stages (Table 4.16). The initial stage recorded the lowest ET_c (0.50 mm day⁻¹) followed by development stage (1.77 mm day⁻¹) at 40-70 DAS and end stage (1.9 mm day⁻¹). The mid stage at 70 to 120 DAS recorded the highest ET_c (4.36 mm day⁻¹). The ET_o values in different growth stages viz. initial stage (0 to 40 DAS), development stage (40 to 70 DAS), mid stage (70 to 120 DAS), end stage (120 to 140 DAS) were 1.55 mm day⁻¹, 1.43 mm day⁻¹, 3.28 mm day⁻¹ and 4.75 mm day⁻¹, respectively. K_c values were 0.32, 1.24, 1.33 and 0.40 in initial stage (0 to 40 DAS), development stage (40 to 70 DAS), mid stage (70 to 120 DAS), end stage (120 to 140 DAS), respectively.

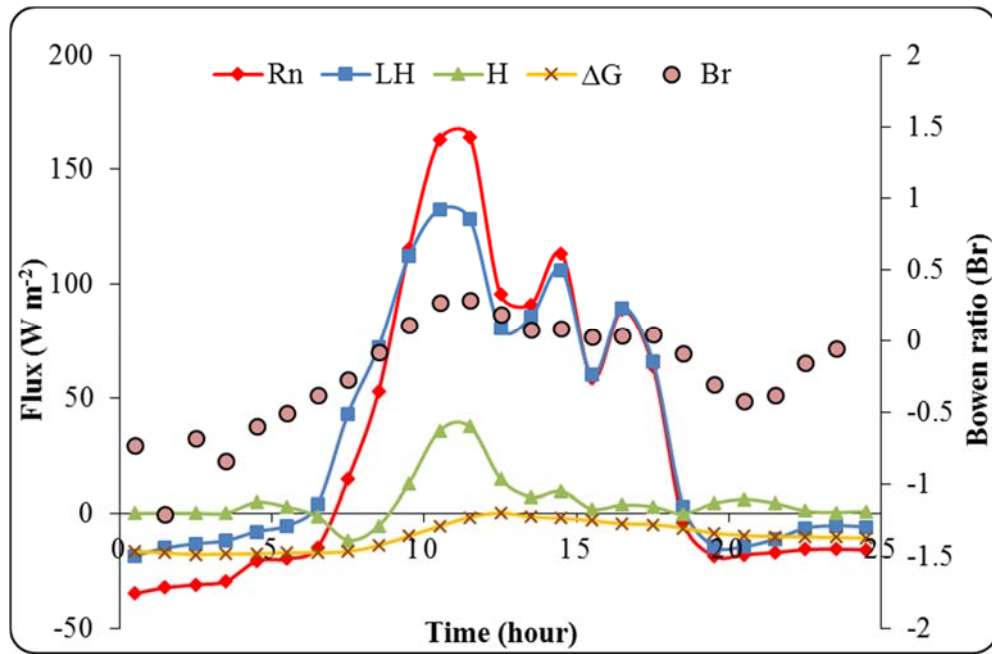
Table 4.16: Variation of ET_c, ET_o and K_c in wheat crop (*rabi*, 2017-18).

Development stages	ET _c (mm day ⁻¹)	ET _o (mm day ⁻¹)	K _c
Initial stage (0-40)	0.49	1.55	0.32
Development stage (40-70)	1.77	1.43	1.24
Mid stage (70-120)	4.36	3.28	1.33
End stage (120-140)	1.9	4.75	0.40

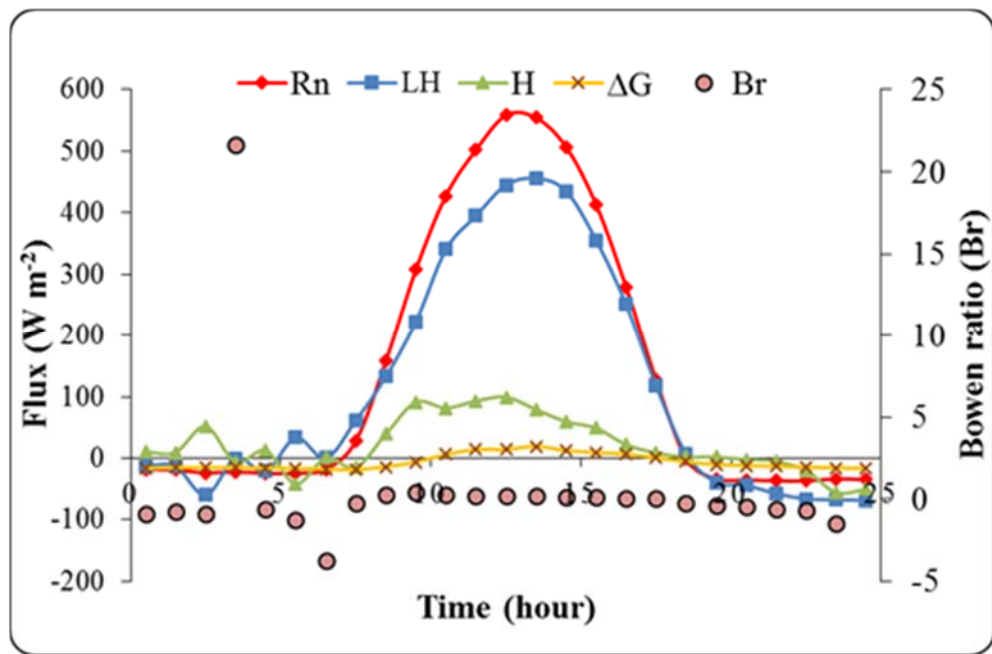
4.10. Relationship of LAI with G/Rn ratio

The soil heat flux followed a consistent pattern throughout the crop growing season. As the G/Rn ratio (mid-day at 12.30 hrs) is not varying much, a relationship was developed with LAI of each crop in both the crop growing season. The Rn varies highly from 22.16 W m⁻² to 527.84 W m⁻². The variation of G was - 9.96 W m⁻² to 54.69 W m⁻² during *kharif*, 2017. The relationship of G/Rn and LAI was presented in Fig. 4.35. Initially G/Rn ratio was minimum and it decreased as crop grown vigorously, and reached minimum when LAI was highest (4.5) at siliking stage. After that with decreasing LAI, the G/Rn ratio increased upto maturity (Fig. 4.35).

During *rabi*, 2017-18 the Rn varied from 89.76 W m⁻² to 456.96 W m⁻². The G varied from -1.18 W m⁻² to 82.00 W m⁻². In wheat season also the relationship was similar to maize crop season. Initially G/Rn was more and decreased upto 90 DAS (Flowering stage). After that the G/Rn ratio increased with crop senescence (Fig. 4.36).

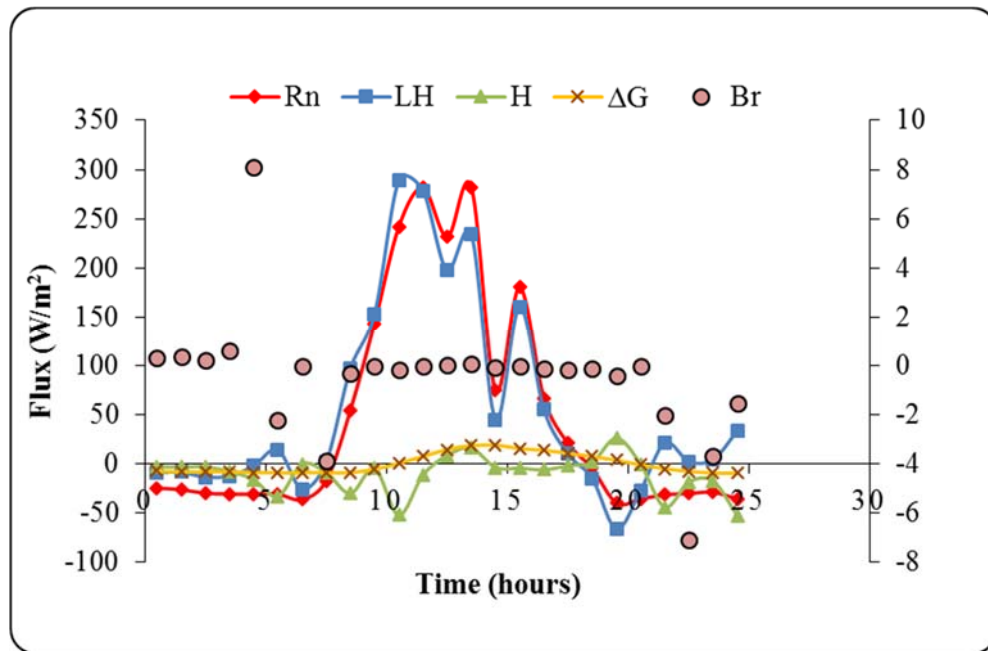


(a)

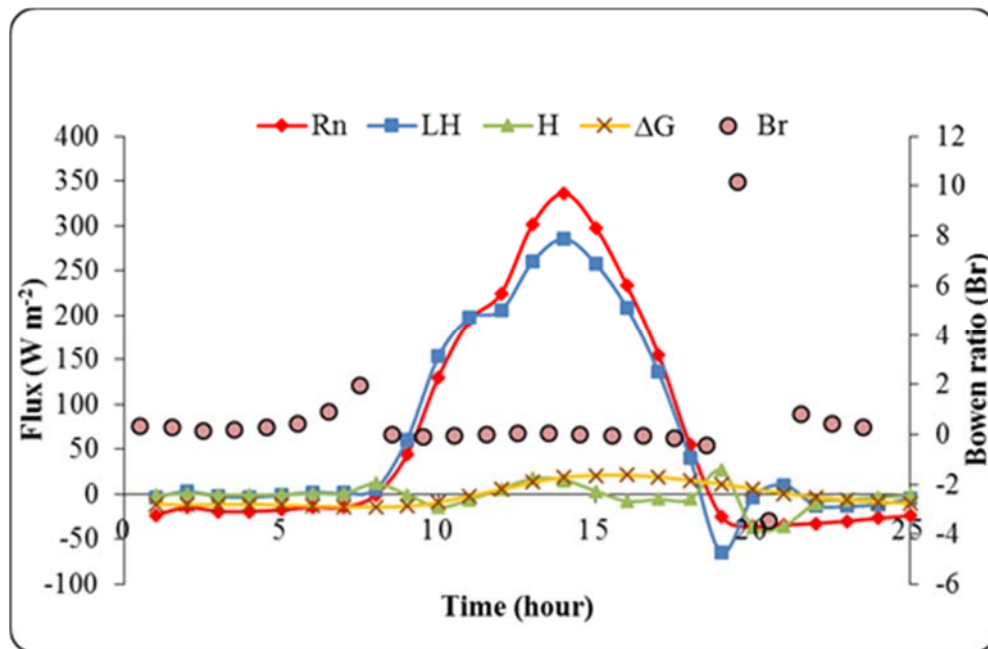


(b)

Fig 4.31 Trend of energy balance and bowen ratio for (a) a cloudy day and (b) cloud free day over maize crop during *kharif*, 2017



(a)



(b)

Fig 4.32 Trend of energy balance and bowen ratio for (a) a cloudy and (b) cloud free day over wheat crop during *rabi*, 2017-18

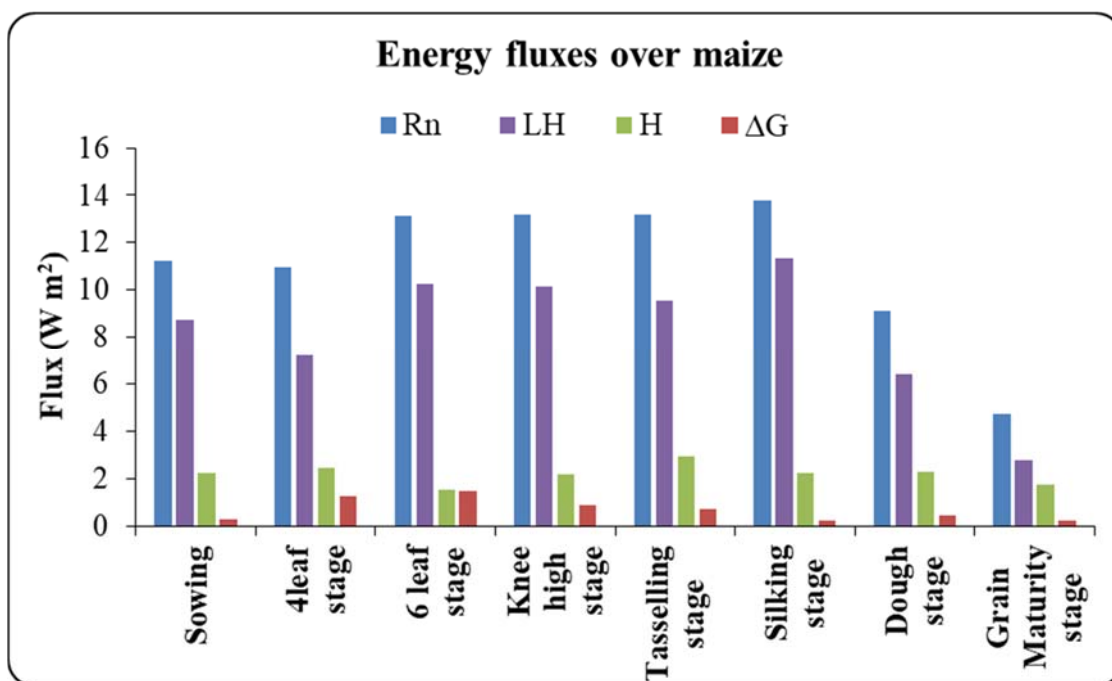
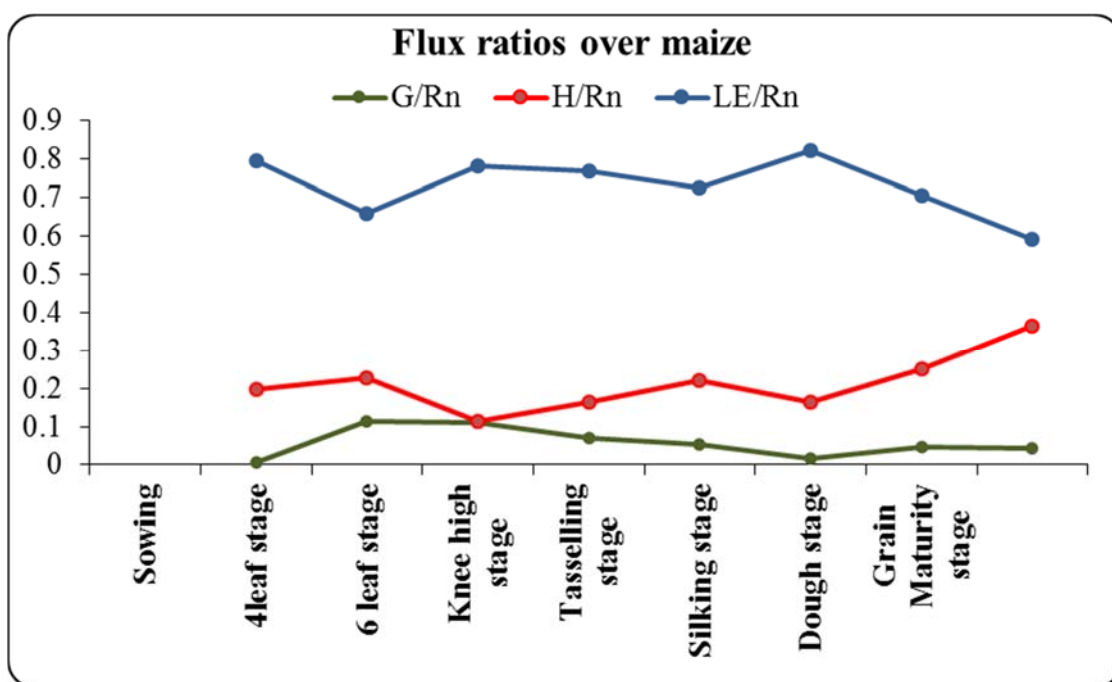


Fig 4.33 Seasonal trend of of energy balance over maize crop during *kharif*, 2017

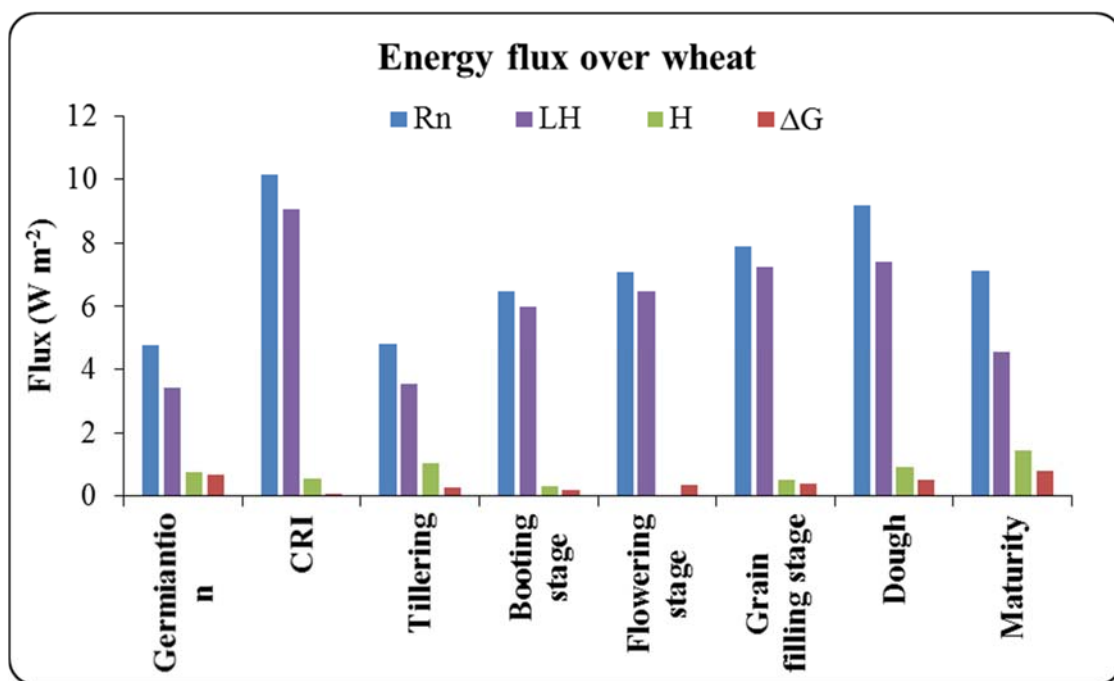
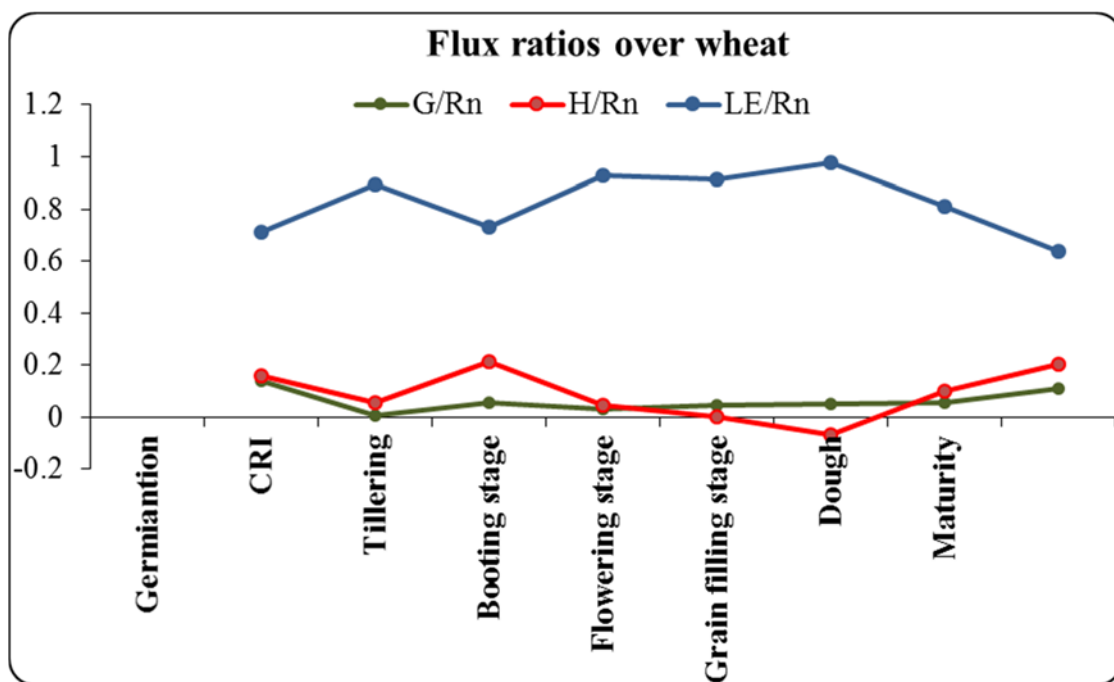


Fig 4.34 Seasonal trend of of energy balance over wheat crop during *rabi*, 2017-18

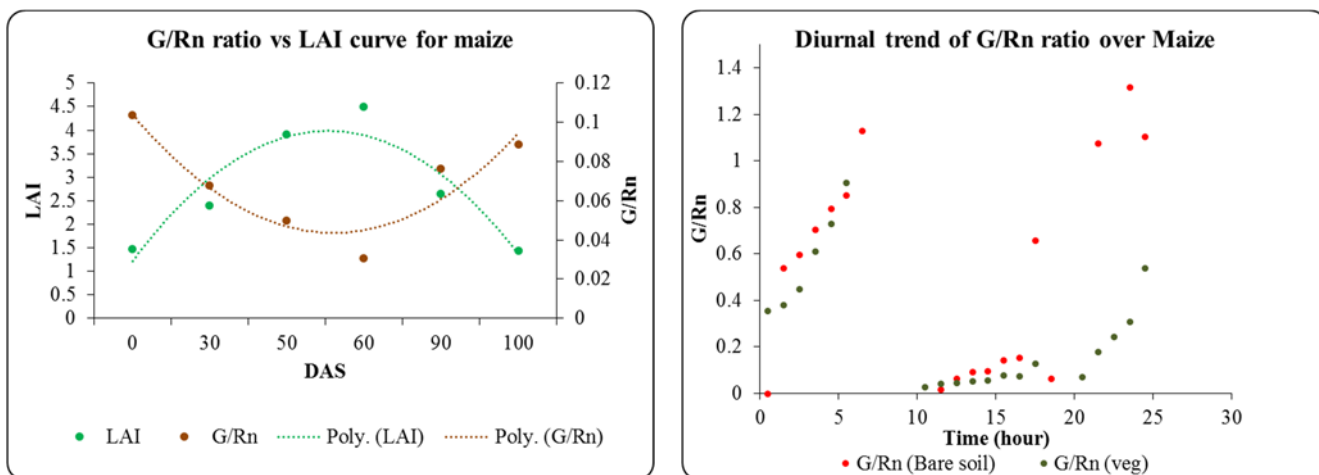


Fig 4.35 Seasonal and diurnal pattern of G/Rn ratio for maize crop during *kharif*, 2017

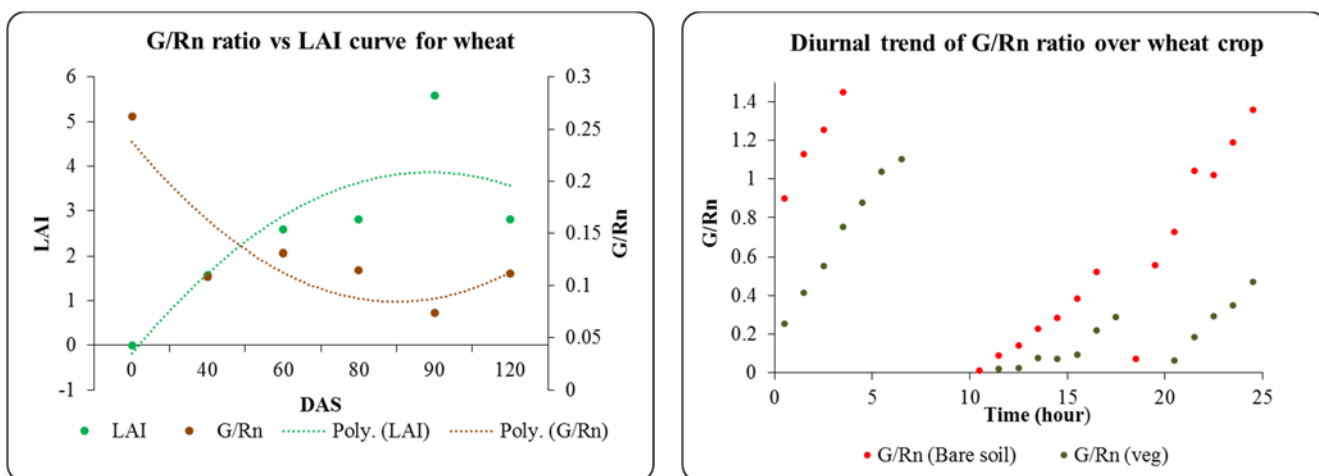


Fig 4.36 Seasonal and diurnal pattern of G/Rn ratio for wheat crop during *rabi* 2017-18

5. DISCUSSION

Weather and climate are the affects crop production to a very large extent. But specifically, the microclimate is the most influencing factor as it depends on local environment as well as with crop management practices. Energy balance and partitioning of its components are crucial for hydrology and regional climate modeling to address the global food problems (Brown and Halweil, 1998). Thus it is very important to calculate the energy balance components so that we can understand the dynamic changes, can monitor environmental evaporative processes and understand the factors affecting the different energy balance components in a regional scale. Many scientific studies reported on the controlling factors of stomatal conductance or transpiration control mechanism due to availability of sophisticated instruments like parameters (e.g. Shuttleworth and Wallace, 1985; Jones, 1992), and, many studies are there on micrometeorological studies for evapotranspiration measurements (e.g. Steduto and Hsiao, 1998a–d; Villalobos *et al.*, 2000), or modelling studies (e.g. Alves and Pereira, 2000; Calvet, 2000; Mo and Liu, 2001). Different international bodies formed to study the flux network at the regional level such as GEWEX/GAME, IGBP/FLUXNET, ASIAFLUX, etc. But the major problem in these studies is the up scaling from leaf to plant and thereafter plant to canopy and ultimately canopy to the landscape. Therefore, a better understanding of energy balance partitioning and process controlling evapotranspiration for entire landscape is need of the hour. Understanding of seasonal dynamics of energy balance over entire crop growth period where a lot of variations are occurred in soil moisture as well as in air temperature needs to explore more (Viterbo and Beljaars, 1995). High temporal resolution data are essential for understanding energy partitioning processes and ET calculation. In the present study, the multilevel weather station was employed to measure energy balance components in a maize-wheat rotation. Mainly Bowen ratio approach experimented in grain fields and restricted to few days or for a week

duration (Baldocchi, 1994 a,b). The main reason behind this is difficulty in maintenance of tower though installation is easy and fetch requirement is less (20:1). Bowen ratio method can be used to calculate seasonal as well as annual changes (Shen *et al.*, 2002; Zhang *et al.*, 2002).

In evapotranspiration studies the influence of crop height is enormous particularly in semi-arid regions of northern India. More aerodynamic roughness occur for taller crop which ultimately extract more energy from atmosphere. Taller crops extract more energy in the form of sensible heat than short crop where sensible heat advection is occurring. Oncley *et al.*, 2007 and Irmak *et al.*, 2014 also reported that with the increase of alfalfa crop height the water evaporated is also increasing. Brakke *et al.*, 1978 reported that ET was more in wheat field compare to pine forest. Advection plays a major role in modifying the pattern of energy balance and ET also increased by advection in semi-arid region (Rosenberg, 1969; Hanks *et al.*, 1971; Langet *et al.*, 1974).

The thickness of boundary layer and zero plane displacement (Z_0) is determined by the crop height. So the crop height determined the position of different sensors in the boundary layer. Taller crop increases the mixing by increasing turbulence. In the active growth phases, a rapid increase of crop height increases aerodynamic roughness which leads increasing ET from the crop. As the crop height is almost stagnant towards physiological maturity the ET was less in later stages.

Leaf area is dependent on length and breadth of the leaf. Increasing leaf area may be due crop was trying to maintain the growth under the reduced light by allocating more photosynthesis. One of the most reliable index of crop productivity is LAI. Plant is able to utilize more radiation particularly in vegetative stage when LAI increases rapidly thus increase the carbohydrate synthesis. LAI decreased later stage of the crop mainly due to senescence of crop towards maturity.

The dry matter accumulation is largely dependent on photosynthesis surface. The rate of dry matter production is slow in initial growth stages. The rapid increase

dry matter production is observed in active growth stages. The dry matter accumulation after flowering stage is mainly due to earhead development. Up to harvest crop continues to accumulate dry matter but the rate is slow.

The yield of a crop is a function of total incident PAR (TIPAR), a fraction of incident radiation intercepted by any crop (fIPAR), radiation use efficiency (RUE) and harvest index (HI). Crop yield and production is highly dependent on all these factors as alteration of these factors changes yield and production. Scientists (Zhang *et al.*, 2014; VanLoocke, 2012; Bhatia *et al.*, 2013 and Feng *et al.*, 2011) reported yield of different crops and HI.

Inside the crop canopy, the temperature was lower up to a certain height. Above that temperature was increased. Atzema (1993) reported that the temperatures inside the wheat crop at various heights are variable in comparison to the ambient environment. Similar results were also achieved by Sentelhas *et al.* (1993) and Yan & Zhang (2007). Tompkins *et al.* (1993) presented that inside a densely sown wheat canopy temperature was lower up to 1.5 °C during daytime. The temperature difference inside the vertical canopy profile may be substantial during the time when the sun is at zenith. Kredl *et al.* (2012) also reported that inside a wheat crop canopy the temperature difference between ground level and effective crop height was around 6°C in the wheat canopy and 9 °C in the rape canopy. According to Kredl *et al.* (2012) humidity at 2 meters above the crop (rape and wheat) canopies was also higher in comparison to the meteorological observatory data. The humidity at 2 meters above the grass canopy was 30%, the wheat crop humidity was 43% and rape's humidity was 40%. The higher air humidity resulted in the crop canopy influence on the microclimate of the surrounding atmosphere.

In maize crop, the energy balance components are following the same trend as R_n in sowing time (0 DAS). As the soil was dry, the sensible heat flux was away from the surface whole day which indicates soil surface is the source of sensible heat generation. The soil evaporation contributes towards latent heat flux as there was no

crop canopy to transpire. So moisture loss from the bare soil is the only source of LE. There was always a time lag observed between the maxima of R_n and H & G . The higher contribution of H is mainly due to less crop cover (low LAI). The contribution of evaporation from soil is dominant over plant transpiration, which contributes more to LE. The maize crop canopy got warmer after 15.00 hrs thus the canopy get hotter. Some amount of water from the canopy in the form of transpiration keeps the leaf cooler. The air temperature recorded by the upper sensor was higher than the lower sensor. Throughout the day temperature gradient was positive. In knee-high stage, the air temperature was higher (around 32.9°C) when the canopy temperature was lower as transpiration was more. The value of H changed from 2.54 to 106.13 $W\ m^{-2}$. The vapor pressure increased after 14.30 hrs but the vapor pressure gradient at the same time started decreasing. At this stage, the LAI was around 2.40 and plant height was 240 cm. The soil surface was moist as irrigation was given 3 days earlier. In tasselling stage, the sensible heat flux (H) was positive throughout the day, but there was no advection. In the afternoon the temperature gradient increased as air mass passing over the crop canopy was warm but the canopy was cool due to transpiration. The crop surface-based inversion condition was developed as the availability of large evaporating surface and increased mixing due to higher LAI and higher plant height. In silking stage, the higher percentage of LE indicated the presence of other source of energy. The LE value was more in the afternoon compared to morning time. The sensible heat advection was observed throughout the day. The magnitude of advection increased in the afternoon thus the LE values increased over net radiation. This is evident from temperature and vapour pressure gradient. Similar type of results was also observed by Kim (1989) and reported that in anthesis stage the values of H varied from 10 to 140 $W\ m^{-2}$ while latent heat flux peak was at 12.00 hrs. At physiological maturity, the sources for LE would have been the drying of crop and evaporation from the deeper layer of the soil profile as some cracks was developed on the soil surface. The temperature as well as vapour pressure gradient both remain negative thus giving a positive Bowen ratio. The Bowen ratio was sometimes more than 1. Even though

the daytime temperature were less than 35°C, the sensible heat advection was not much noticed as the crop had dried up to a great extent and contributed towards sensible heat flux. The instantaneous midday Bowen ratio and EF was also estimated by Crago and Brutsaert (1996) and concluded that the constant evaporative fraction (EF) assumption is better to the constant Bowen ratio assumption for estimation of daytime evaporation. Findings of Steduto (1998) also confirmed our results. For unstable conditions during daytime, an error appear for negative temperature gradient with a downward sensible heat flux (i.e. $H < 0$). This type of situation occur just after irrigation and precipitation. But BREB methods not working in the early morning, just after sunset and during the night as net radiation and heat flux turned from positive to negative (Perez *et al.*, 1999).

Fluctuations were observed in all measured components of energy balance due to cloud cover at the time of convective conditions. Oke, 1987 also observed that in the cloudy condition the crop albedo varied widely and the average albedo in their case was 0.15 which is comparable with the dry soil surface. Presence of low cumulus type cloud the sensible heat flux and soil heat flux dropped. During cloudy days cloud masked the solar disk fully (Jegade *et al.*, 2002). The convective cloud cover severely influenced the radiation received and energy balance highly influence

Most of the energy is used in LE compare to other components. Partitioning of R_n to S was always less than LE. During *kharif*, 2017, air temperature was decreased towards maturity of the crop. As the temperature was decreased at maturity the contribution of S is also low. This was due to most of the energy available from net radiation and also sensible heat (S) advection was utilized in latent heat (LE). At the later stages when the crop growth was more, LAI was more intercepted more radiation energy thus very less amount of radiation reached the ground and reduced the soil temperature. At the maturity when senescence increased the radiation penetration increased and reached the soil surface which resulted in more contribution of soil heat flux. At an early stage, sensible heat flux during *kharif*, 2017 was more as

crop cover was not there. In wheat crop initially, S was higher but decreased thereafter and increased towards maturity. The contribution of advection was more in the evening time when the air was warmer, though the net radiation was negative. The sensible advection sometimes continued after sunset also in wheat season. During crop growing season LE was more when crop canopy was there. Even ET was more towards the end of the crop season, though the LAI was decreasing. Similar type of result also reported by Johnson *et al.*, (1981) and Kim *et al.*, (1989) that LE was more than 60% towards the end of the crop season. These type of results are mainly due to earhead and awns of the wheat crop.

In general, in both the crops the daytime ET values were less than 24 hours ET values. The difference of ET_c at dough stage was mainly due to sensible heat advection which continued after sunset also. Thus ET_c values increased. In earlier or initial stages In earlier growth stages very less difference was observed between 24 hours ET, was mainly due to advection was less and subsided after setting of the sun. Loss of data for estimating of ET_c particularly for daytime was less (only 8%) in comparison to 24hours estimation. The PET mainly depends on the atmosphere and there is no connection with the transpiring surface. As the leaf surface and earhead transpired in huge rate, the flowering stage was having maximum water demand compare to other stages. The convective mixing of the upper layer of warm air and lower of cool air was present. Our results are at par with the findings of Jadhav, 1989. His K_c values varies from 0.93 at CRI stage to 1.86 at flowering. The K_c values reported by FAO (1998) are in initial stages 0.3-0.40 (15 to 20 DAS), for development stage, 0.7 - 0.8 (25 to 40 DAS), for the mid-season 1.05 – 1.2 (50 to 65 DAS), for the late season 0.65 – 0.70 (65 to 90 DAS) and at maturity 0.2 – 0.25, which are very close to our findings. Nag *et al.* (2014) and Tyagi *et al.* (2000) calculated the ET_o for different crops. Their findings are also similar to our result. Kondoh and Higuchi (2001) reported that the ET from grass responds linearly to the NDVI throughout the growth period. Thus evaporative fraction (EF) is linearly dependent on LAI upto senescence. Many experiments in the literature suggest that

when soil water is not limiting factor there is no correlation between soil water content and EF (Nichols and Cuenca, 1993; Zhang and Lemeur, 1995). LAI slightly influence ET. When canopy cover is more, the Bowen ratio of crop- soil system is linearly related with soil moisture thus Bowen ratio will increase as the soil becomes drier. This is because soil water status can affect leaf stomatal conductance (Gollan *et al.*, 1986; Jones, 1992; Shen *et al.*, 2002), through which the evapotranspiration of the whole canopy is influenced. Thus, the balance between sensible and latent heat will be changed.

The soil heat flux was not varied much throughout the crop growing season. Thus the relationship of G/Rn with LAI followed a consistent trend. The ratio was initially high decreased in growing season of crop and reached lowest when the crop had highest LAI. After that it increased up to maturity of crop. Similar results were reported by Shen *et al.* (2004), which supports our findings. They also reported that the mid-day G/Rn ratio has a strong relationship with LAI, which decreases when LAI was less. Zang *et al.* (2004) also reported that G/Rn ratio for wheat crop (at jointing to senescence is approximately 10 to 13% which is higher than maize crop (5-7%).

6. SUMMARY AND CONCLUSION

Proper assessment is required for efficient natural resources management. One of the major factor in field water balance is evapotranspiration (ET). It is a component of the hydrological cycle whose accurate calculation at the local and regional scale is needed to achieve an appropriate management of water requirements, in irrigation design and scheduling, watershed hydrology, mechanistic crop growth models and other models that attempt to simulate the soil water budget.

Bowen ratio energy balance (BREB) method is a micrometeorological method by combining Bowen ratio with energy balance components of earth. This method has been used to estimate sensible heat and latent heat and mass (ET) fluxes to quantify water use of crop, determination of crop coefficients, evaluate crop water use models, measurement of emission of trace gases like methane and nitrous oxide etc., from soil or crop surface and to measure carbon dioxide assimilate rate in crops

In this study, a field experiment was conducted on maize (variety: PMH-1) and wheat (variety: HD 2967) in the main experimental farm of ICAR during *kharif*, 2017 and *rabi* 2017-18. Homogeneous crop was grown in both the season and micrometeorological tower was installed inside the crop field. Micrometeorological tower is having temperature, humidity, wind speed in five levels (0.5 m, 1m, 2m, 4m, and 8m), net radiometer at 2m height, PAR sensor at 2m height, wind vane at 2m height, soil moisture & soil temperature at three different depths (5cm, 15 cm, 25 cm) and soil heat flux plate at 2 depths (5 cm and 15 cm). Weather data of IARI farm were collected from the agromet Observatory, ICAR-IARI, New Delhi. Micrometeorological parameters like canopy temperature (using IR thermometer) and intercepted PAR (using line quantum sensor) were measured at 10 days interval. Intercepted photosynthetically active radiation (IPAR) was converted into fractional IPAR (fIPAR). Crop biophysical parameters like LAI (by using canopy analyzer), above ground biomass, were also measured at 10 days intervals. Plant height were also measured at different DAS throughout the crop growth period. Soil moisture was also monitored in this study by gravimetric method. Crop phenology was recorded biweekly for maize and wheat crop. Various calculations were done using Microsoft Excel package and statistical analysis was done by using online SAS package.

During *kharif* 2017 sowing was done on 19th July. Cultivar PMH-1 emerged in 9 - 10 DAS. There was no variation in phenological stages initially. Maize matured at 102 DAS. Wheat crop was grown in *rabi* 2017-18. Crop was sown on 24th November, 2017. Cultivar HD-2967 germinated in 6-7 days. CRI stage appeared in 23 DAS. Harvesting was done at 140 DAS. Highest LAI of maize was 4.50 at 80 DAS with a CV varied from 5.74% to 16.35 % and CI varied from 0.14 to 0.25. Subsequently, it decreased with crop maturity. In *rabi* season, Leaf area index (LAI) of wheat crop varied among different observations (Table 4.5). LAI increased initially and reached highest (5.58) in 90 DAS. During *kharif* 2017, maize crop produced highest biomass (19.27 t ha⁻¹) in 108 DAS. During *rabi* 2017-18, wheat crop accumulated 13.25 t ha⁻¹ in different observations. Yield attributes of maize crop were collected at harvest. No. of row per cob was varied from 12.9 to 13.9, No. of grains per row varied from 25 to 30.1, test weight was varied from 213.9 to 222.1, cob length was varied from 12.9 to 13.2 and cob girth varied from 11.3 to 11.9. During *rabi*, 2017-18 (wheat crop) the data of yield attributes varied among different observations. No. of effective tillers per plant were varied from 4-5, Spike length was varied from 10.00-11.00 and test weight was varied from 25.84 to 27.60. Mean grain yield of maize crop recorded 5.66 t ha⁻¹ during *kharif*, 2017. Highest stover yield recorded was 12.63 t ha⁻¹ and highest harvest index was 31.62%. During *rabi* season 2017-18, wheat grain yield varied from 4.18- 4.32 t ha⁻¹. The mean grain yield observed was 4.17 t ha⁻¹. Straw yield were varied from 6.97 to 8.50 t ha⁻¹ among different observations. Highest harvest index was recorded 37.49. The TIPAR was 663.59 MJ m⁻² and 597.64 MJ m⁻² for maize and wheat crop, respectively. Radiation Use Efficiency (RUE) on account of biomass accumulation was more in maize than wheat crop. The RUE on account of biomass accumulation was higher under in maize crop (2.74 g MJ⁻¹) than wheat crop (2.07 g MJ⁻¹). Similar trend was also observed in RUE_y. The RUE for yield was lower in wheat (0.70 g MJ⁻¹) than comparison to maize crop (0.85 g MJ⁻¹).

In soil moisture varied throughout the crop growing season. Initially soil moisture was low and varied around 15% in all three depths. On 21 DAS the crop received 61 mm of rainfall and the soil moisture increased after that. The soil moisture at 15 cm depth was always more than other two depths (5 cm and 25 cm). On 24th August, 2017 (37 DAS) crop received 61.4 mm of rainfall and soil increased to 24.14%

at 15 cm depth. There were two rainfall events on 19th August, 2017 and 24th August, 2017. On 1st September, 2017, the crop received another 45.6 mm of rainfall and the soil moisture of 15 cm depth recorded 26.88%. On 23rd September, 2017 the crop received 136.8 mm of rainfall. In *rabi*, 2017, not even a single rainy day was observed. A total of 3.37 mm rainfall was recorded but no rainy day was there, only 15th week received 1.5mm rainfall. Crop was grown in under irrigation. Peak of the soil moisture observed after irrigation only. Soil moisture was more at 15cm soil depth compare to 5 cm and 25 cm.

Wind, temperature and humidity inside the maize and wheat crop varied widely. In general wind speed was more in noon time than morning and night time. Temperature was more inside the crop canopy from ground surface. Humidity was more inside the crop canopy.

During the sowing stage of maize crop the maximum R_n and were 468.8 $W\ m^{-2}$, 353.3 $W\ m^{-2}$ at 13.30 hrs. There was a time lag to reach the maxima in case of H and G. The maximum H was 119.1 $W\ m^{-2}$ at 14.30 hrs and G was 34.6 $W\ m^{-2}$ at 15.30 hrs, respectively. In four leaf stage of maize the R_n and LE were reached the maxima at 13.30 hrs and the values were 492.16 $W\ m^{-2}$ and 329.2 $W\ m^{-2}$, respectively. The sensible heat flux (111.0 $W\ m^{-2}$) and soil heat flux (72.3 $W\ m^{-2}$) reached a peak at 14.30 hrs and declined thereafter. The maxima of R_n and LE was at 12.30 hrs and the values were 570.2 and 438.1 $W\ m^{-2}$, respectively at knee high stage. At tasseling stage the peak of R_n reached at 13.30 hrs and the value was 533.76 $W\ m^{-2}$. At silking stage the crop was reached a height of 1.56m and the LAI reached around 4.0. Silking stage occurred around 15th September, 2017. The R_n varied from 27.88 to 558.08 $W\ m^{-2}$ and the peak value reached at 12.30 hrs. In dough stage the partitioning of R_n into LE, H and G were 83%, 14% and 3%, respectively. At physiological maturity the maximum R_n was 226.24 $W\ m^{-2}$ at 13.30 hrs and its partitioning into LE, H and G was 50%, 38% and 12%, respectively.

In *rabi*, 2017-18 at sowing the partitioning of energy in LE, H and G at time of maximum R_n (13.30 hrs) was in decreasing order of 70.7%, 18.5% and 10.8%, respectively. At CRI stage of *rabi* (wheat) 2017-18 the highest value of R_n recorded was 504.96 $W\ m^{-2}$ and its partitioning into LE, H and G was 82.2%, 9.7% and 4.9%, respectively. The maxima of R_n and latent heat flux (LE) was occurred at 12.30 hrs and

the values were 260.28 W m^{-2} and 191.01 W m^{-2} , respectively at tillering stage of wheat (*rabi*, 2017-18). During *rabi* 2017-18, the partitioning of R_n into LE was 84.97%, H was 4.7% and G was 5.67%. Moist soil contributed more LE compare to H and G. The soil moisture availability also reduced the H value. The contribution G was low due to higher LAI. During *rabi* 2017-18, at harvest the R_n fluxes followed the same trend and reached peak at around 13.30 hrs. The highest value of R_n recorded was 328.32 W m^{-2} and its partitioning into LE, H and G was 57.58%, 19.76% and 13.06%, respectively. The sensible heat flux reached its peak at 13.30 hrs and the value was 77.55 W m^{-2} . In a cloudy day at silking stage all the components of energy balance varied through the day. The peak values of R_n , LE, H and G were 164.32 W m^{-2} , 132.87 W m^{-2} , 37.54 W m^{-2} and 0.15 W m^{-2} , respectively. In flowering stage of wheat crop on a cloudy day the peak R_n , LE, H and G was 278.71, 281.65, 15.23 and 18.73, respectively. The values of ETc at different growth stages of maize viz. initial stages (0 to 20 DAS), development stage (21 to 45 DAS), mid stage (46 to 85 DAS) and end stage (86 to 105 DAS) were 2.29 mm day^{-1} , 3.92 mm day^{-1} , 4.78 mm day^{-1} , and 2.08 mm day^{-1} , respectively. The initial stage of wheat crop recorded the lowest ETc (0.50 mm day^{-1}) followed by development stage (1.77 mm day^{-1}) at 40-70 DAS and end stage (1.9 mm day^{-1}). The mid stage at 70 to 120 DAS recorded the highest ETc (4.36 mm day^{-1}).

The salient finding of this study are:

- ❖ Taller crop increases the mixing by increasing turbulence. In the active growth phases a rapid increase of crop height increases aerodynamic roughness.
- ❖ Inside the crop canopy, the temperature, humidity and wind speed were lower up to a certain height. Above that all were increased.
- ❖ At initial stages the soil evaporation contributes towards latent heat flux as there was no crop canopy to transpire.
- ❖ Most of time R_n reached peak at noon time (12:30 hrs)
- ❖ Most of the energy is used in LE compared to other components. Partitioning of R_n to H was always less than LE.
- ❖ There was always a time lag observed between the maxima of R_n and H & G.
- ❖ At initial stages contribution of evaporation from soil is dominant over plant transpiration, which contributes more to LE.

- ❖ The contribution of advection was more in the evening time when air was warmer though the net radiation was negative.
- ❖ Fluctuations were observed in all measured components of energy balance due to cloud cover at the time of convective conditions.
- ❖ In both the crops the day time ET values were more than 24 hrs ET values.
- ❖ Relationship with G/R_n with LAI was consistent throughout the crop growth.
- ❖ G/R_n was lowest when crop LAI reached its highest value, in case both maize and wheat crop.

Surface energy fluxes over irrigated maize-wheat using Bowen Ratio Energy Balance method

Abstract

Bowen ratio energy balance (BREB) method is a micrometeorological method by combining Bowen ratio with energy balance components of earth surface. In this study, a field experiment was conducted on maize (variety: PMH-1) and wheat (variety: HD 2967) in the main experimental farm of ICAR during *kharif* 2017 and *rabi* 2017-18. Homogeneous crop was grown in both the season and micrometeorological tower was installed inside the crop field. Micrometeorological tower had temperature, humidity, wind speed at five horizontal levels (0.5m, 1m, 2m, 4m, and 8m above ground), net radiometer at 2m height, PAR sensor at 2m height, wind vane at 2m height, soil moisture & soil temperature at three different depths (5cm, 15cm, 25cm) and soil heat flux plate at two depths (5cm and 15cm). During *kharif* 2017, sowing was done on 19th July. Cultivar PMH-1 emerged in 9 - 10 DAS. There was no variation in phenological stages initially. Maize matured at 102 DAS. Wheat crop was grown during *rabi* 2017-18. Crop was sown on 24th November, 2017. Cultivar HD-2967 germinated in 6-7 days. CRI stage appeared at 23 DAS. Harvesting was done at 140 DAS. Highest LAI of maize was 4.50 at 80 DAS with a CV varied from 5.74% to 16.35 % and CI varied from 0.14 to 0.25. Mean grain yield of maize crop was recorded 5.66 t ha⁻¹ during *kharif*, 2017. During *rabi* season 2017-18, wheat grain yield varied from 4.18- 4.32 t ha⁻¹. The mean grain yield was observed 4.17 t ha⁻¹.

During the sowing stage of maize crop the maximum Rn was 468.8 W m⁻² at 13:30 hrs. There was a time lag to reach the maxima in case of H and G. The maxima of Rn and LE was at 12:30 hrs and the values were 570.2 and 438.1 W m⁻², respectively at knee high stage. At tasseling stage the peak of Rn reached at 13:30 hrs and the value was 533.76 W m⁻². At silking stage the crop reached a height of 1.56m and the LAI reached around 4.0. At physiological maturity the maximum Rn was 226.24 W m⁻² at 13:30 hrs and its partitioning into LE, H and G was 50%, 38% and 12%, respectively. In *rabi* 2017-18, at sowing the partitioning of energy in LE, H and G at time of maximum Rn (at 13:30 hrs) was in decreasing order of 70.7%, 18.5% and 10.8%, respectively. At CRI stage of *rabi* (wheat) 2017-18, highest value of Rn recorded was 504.96 W m⁻² and its partitioning into LE, H and G was 82.2%, 9.7% and 4.9%,

respectively. During *rabi* 2017-18, the partitioning of Rn into LE was 84.97%, H was 4.7% and G was 5.67%. Moist soil contributes more LE in comparison to H and G. The soil moisture availability also reduced the H value. The contribution G was low due to higher LAI. The highest value of Rn recorded was 328.32 W m^{-2} and its partitioning into LE, H and G was 57.58%, 19.76% and 13.06%, respectively. The sensible heat flux reached its peak at 13:30 hrs and the value was 77.55 W m^{-2} . In a cloudy day at silking stage all the components of energy balance varied throughout the day. The initial stage of wheat crop recorded the lowest ETc (0.50 mm day^{-1}) followed by increase in development stage (1.77 mm day^{-1}) at 40-70 DAS and end stage (1.9 mm day^{-1}). The mid stage at 70 to 120 DAS recorded the highest ETc (4.36 mm day^{-1}). In case of both crops, G/Rn ratio was lowest when crop LAI was highest.

बोवेन अनुपात ऊर्जा संतुलन विधि का उपयोग करके सिंचित मक्का-गेहूं में भूतल ऊर्जा प्रवाह

सार

बोवेन अनुपात ऊर्जा संतुलन (बीआरईबी) विधि, पृथ्वी के ऊर्जा संतुलन घटकों के साथ बोवेन अनुपात को जोड़कर निर्मित एक माइक्रोमैटोरोलॉजिकल विधि है। इस अध्ययन में खरीफ 2017 और रबी 2017-18 मौसम के दौरान आईसीएआर के मुख्य प्रयोगात्मक खेत में मक्का (किस्म पी.एम.एच. -1) और गेहूं (किस्म एच.डी. 2967) पर एक मैदानी प्रयोग आयोजित किया गया। दोनों मौसम में सजातीय फसल उगाई गई और फसल क्षेत्र के अंदर माइक्रोमैटोरोलॉजिकल टावर स्थापित किया गया। माइक्रोमैटोरोलॉजिकल टावर में तापमान, आर्द्रता, हवा की गति को मापने वाले सेंसर पांच स्तरों (0.5 मीटर, 1 मीटर, 2 मीटर, 4 मीटर, और 8 मीटर) पर स्थापित हैं, दो मीटर ऊंचाई पर नेट रेडियोमीटर, PAR सेंसर और पवन वेन सेंसर स्थित हैं। मिट्टी नमी और मिट्टी का तापमान को मापने वाले सेंसर तीन गहराई पर (5 सेमी, 15 सेमी, 25 सेमी) तथा मिट्टी गर्मी प्रवाह प्लेट दो गहराई (5 सेमी और 15 सेमी) पर स्थित हैं। मक्का की बुवाई 19 जुलाई, खरीफ मौसम 2017 के दौरान की गयी। कल्टीवार पीएमएच -1 मक्का की एक किस्म, को बुवाई के 9 से 10 दिनों के बाद उभरते हुए देखा गया। शुरुआत में फलाद्रमिकी चरणों में कोई बदलाव नहीं था। 102 डी.ए.एस पर मक्का परिपक्व हो गयी। रबी 2017-18 में गेहूं की फसल उगाई गई थी। फसल की बुवाई 24 नवंबर, 2017 की गयी। कल्टीवार एचडी -2967, गेहूं की एक किस्म को 6 से 7 दिनों में अंकुरित देखा गया। सी.आर.आई चरण, 23 डी.ए.एस में दिखाई दिया। 140 डी.ए.एस पर फसल की कटाई की गयी। मक्का का उच्चतम एल.ए.आई 80 डी.ए.एस पर 4.50 था, जिसकी सी.वी. 5.74% से 16.35% और सी.आई. 0.14 से 0.25 तक परिवर्तित देखी गयी। खरीफ मौसम के समय, मक्का फसल की औसतन अनाज उपज 5.66 टन प्रति हेक्टेयर दर्ज की गयी। जबकि 2017-18 के दौरान, गेहूं की अनाज की पैदावार 4.18-4.32 टन हेक्टेयर से भिन्न थी और औसत अनाज उपज 4.17 टन प्रति हेक्टेयर देखी गयी।

मक्का की बुवाई के दौरान अधिकतम आर.एन. 468.8 वाट प्रति मीटर वर्ग, 353.3 वाट प्रति मीटर वर्ग 13.30 बजे पर अभिलेख की गयी। मक्का की नी हाई अवस्था के उच्च स्तर पर एच और जी के मामले में अधिकतम चरम सीमा तक पहुंचने में समय अंतराल था। आर.एन. और एल.ई. की अधिकतमता 12.30 बजे थी और मान क्रमशः 570.2 और 438.1 वाट प्रति मीटर वर्ग था,। तस्सेलिंग चरण में आरएन की अधिकतम मान 13.30 बजे पहुंची और यह मान 533.76

वाट प्रति मीटर वर्ग थी। मक्के की बाली आने की अवस्था पर फसल 1.56 मीटर की ऊंचाई तक पहुंच गई थी और एल.ए.आई. 4.0 के आसपास दर्ज किया गया। मक्का की परिपक्वता अवस्था पर अधिकतम आर.एन. 226.24 वाट प्रति मीटर वर्ग 13.30 बजे मापा गया और एल.ई., एच. और जी. में इसका विभाजन क्रमशः 50%, 38% और 12% था। रबी 2017-18 बुवाई मौसम में अधिकतम आर.एन. (13.30 बजे) के समय एल.ई., एच. और जी. में ऊर्जा का विभाजन क्रमशः 70.7%, 18.5% और 10.8% के क्रम में था। रबी (गेहूं) 2017-18 फसल के सीआरआई चरण में रिकॉर्ड किए गए आर.एन. का उच्चतम मान 504.96 वाट प्रति मीटर वर्ग था और इसकी विभाजन क्रमशः एल.ई., एच. और जी. में 82.2%, 9.7% और 4.9% थी। रबी 2017-18 के दौरान, आर.एन. में एल.ई. का विभाजन 84.97% था, एच. 4.7% था और जी. का 5.67% था। गीली मिट्टी, एच और जी की तुलना में अधिक एल.ई. में योगदान देती है। मिट्टी की नमी की उपलब्धता ने एच मान को भी कम कर दिया है। उच्च एल.ए.आई. के कारण, योगदान जी कम था। रिकॉर्ड किए गए आर.एन. का उच्चतम मूल्य 328.32 वाट प्रति मीटर वर्ग था और इसका विभाजन एल.ई., एच. और जी. में क्रमशः 57.58%, 19.76% और 13.06% था। प्रत्यक्ष गर्मी प्रवाह 13.30 बजे शिखर पर पहुंच गया और मान 77.55 वाट प्रति मीटर वर्ग रहा। मेघाच्छन्न दिन के दौरान मक्के की बाली अवस्था में, ऊर्जा संतुलन के सभी घटकों को परिवर्तित देखा गया। गेहूं की फसल के शुरुआती चरण में सबसे कम ई.टी.सी. (0.50 मिली मीटर प्रति दिन) दर्ज किया गया, इसके बाद विकास चरण (1.77 मिली मीटर प्रति दिन) 40-70 डी.ए.एस में और अंत चरण (1.9 मिली मीटर प्रति दिन) पर दर्ज किया गया। 70 से 120 डी.ए.एस के मध्य चरण में उच्चतम ई.टी.सी. (4.36 मिली मीटर प्रति दिन) अनुमानित किया गया। दोनों फसल का एल.ए.आई. सबसे ज्यादा देखा गया, जब जी और आर.एन. का अनुपात सबसे कम था।

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