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Research paper

Heat wave characterization and its impact on carbon and water vapour fluxes over sugarcane-based agroecosystem

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ABSTRACT

Global climate change expected to exacerbate the temperature extremes and intensity of heat waves in recent decades. The terrestrial biosphere plays a crucial role in absorbing carbon from the atmosphere. Therefore, understanding how terrestrial ecosystems respond to extreme temperatures is essential for predicting land-surface feedbacks in a changing climate. In light of this, a study was conducted to assess the effects of 2022 heat wave [March-May (MAM)] on carbon and water vapour fluxes. This study utilized the measurements obtained from the eddy covariance tower mounted within the sugarcane agroecosystem. The study period (MAM) was characterized into three events: Heat wave event 1 (HE1), Heat wave event 2 (HE2), Non heat wave event (NHE). The variation in carbon and water vapour fluxes, along with meteorological variables, during these events in 2020 and 2022 was further analysed. Our findings indicate that the heat wave caused a decrease in net ecosystem exchange (NEE), leading to an increase in atmospheric CO_2 concentration during HE1, HE2 compared to NHE. In HE1, maximum NEE in 2020 and 2022 was -19.15 $\mu mol\ m^{-2}\ s^{-1}$ and -13.21 $\mu mol\ m^{-2}\ s^{-1}$, respectively. Furthermore, the heat wave events led to a decrease in latent heat flux (LE) and sensible heat flux (H), with changes of up to 5% in LE and 57% in H compared to the same period in 2020. These results highlight the significant impact of the heatwave on both carbon and energy fluxes. Overall, the present study provides a valuable reference for further climate change analysis, specifically focusing on both carbon and energy fluxes within sugarcane ecosystem.

Keyword: Temperature, Heat wave, Agroecosystem, Eddy covariance, Carbon fluxes.

Heat wave is an extreme weather event resulting from the hot conditions in the near-surface atmosphere. It has an adverse impact on agriculture, human health and industrial production (Bhattacharya *et al.,* 2023). Global climate change is credited to enhance the frequency and intensity of the heat waves over Southeast Asia (IPCC, 2021). Global climate change assessments indicate a rise of around 5°C in the global average temperature (T_{avg}) by the end of 21st century, if the emissions of green-house gases are sustained. The global T_{avg} is expected to rise by 3°C even if the Nationally Determined Contribution (NDC) declared by 2015 Paris Agreement are met. T_{avg} in India have risen by 0.7°C during 1901-2018 (Krishnan *et al.,* 2020). Moreover, in a worst case scenario (RCP 8.5), the T_{avg} is projected to rise by 4.4°C over India by the end of 21st century compared to the period between 1976 and 2005. Increase in the temperature will also affect the heat wave intensity (Gorsel *et al*., 2016). The amplification of heat stress is expected to be more prevalent over the Indo-Gangetic region and Indus river basins (Krishnan *et al.,* 2020). Northern Bihar region in Indo-Gangetic plains experienced 103 heat wave days from 1999 to 2015 (Mahdi *et al*., 2020). The number of heat waves increased to 70 days from 1997 to 2009 in the semi-arid climate of Udaipur, Rajasthan (Jemimah *et al*., 2011). Heat waves are usual to the Indian sub-continent during March to May (Kothawale *et al*., 2010; Rohini *et al*., 2016), but the heat wave of 2022 was the most deadly as it started early and extended for a long time.

The heat waves are becoming hotter and in future they will occur more often (Lewis and King; 2015). In recent times, many countries of the world are reporting loss of lives, economic losses and agriculture due to intense heatwaves. Agriculture is dependent on climate, soil and water availability. Heatwave can

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affect crop growth in different ways like root and shoot growth, soil moisture uptake, photosynthesis and respiration. Extreme heat events along with soil moisture deficits could intensify the impact of heat wave on agricultural crops (Seneviratne *et al*., 2010), due to reduced evaporative cooling and increased sensible heat flux (Sheffield *et al.*, 2012). The combination of increased evaporative demand and reduced water availability can intensify stress on agro-ecosystems. The farmers of central and northern India have reported wheat yield losses between 20-60%. This happened as a result of early arrival of heat wave affecting wheat crop during their growth stage, leading to shrivelled grains resulting in huge losses. Many of the ecological processes are very sensitive to the climate extremes (Hanson *et al*., 2006). The extremes in temperature can decrease the carbon sequestration and carbon stocks (Gorsel *et al*., 2016; Arain *et al*., 2022). In future, climate extremes can be critical in shaping the dynamics of ecosystem (Zimmermann *et al*., 2009). Therefore, it is imperative to evaluate and understand the ecosystem responses to the climate extremes.

In India, the direct observations of the ecosystem response to the climate extremes have been lacking until very recently. However, employing the eddy covariance (EC) technique, we conducted a pioneering analysis to examine the influence of extreme temperatures on the carbon and energy fluxes for the sugarcane-based agroecosystem along the Indo-Gangetic Plains. Our study employed EC measurements to initially characterize heat wave events occurring from March to May (MAM) in the study area. Subsequently, we investigated the impact of heat wave on carbon flux (Net ecosystem exchange; NEE) and water vapour fluxes (latent heat flux; LE, sensible heat flux, H). Moreover, we analysed the impact of heat wave on key meteorological variables, including atmospheric carbon dioxide concentration (CO_2), vapour pressure deficit (VPD) and stomatal conductance (Gc) over the sugarcane ecosystem.

MATERIAL AND METHODS

Study area

The dataset from eddy covariance (EC) tower was utilized to assess the carbon dioxide (CO_2) and water vapour fluxes from March to May to evaluate the impact of heat wave on agricultural region. The EC tower is augmented over Saharanpur Flux Site (SFS) in Uttar Pradesh, representing one of the major agricultural region of India (Fig. 1). SFS is located at 29°52′N, 77°34′E, with an elevation of 265 above mean sea level. The site prevails under a sub-tropical climate. The tower was located in the midst of sugarcane crop growing in a hectare area.

Datasets

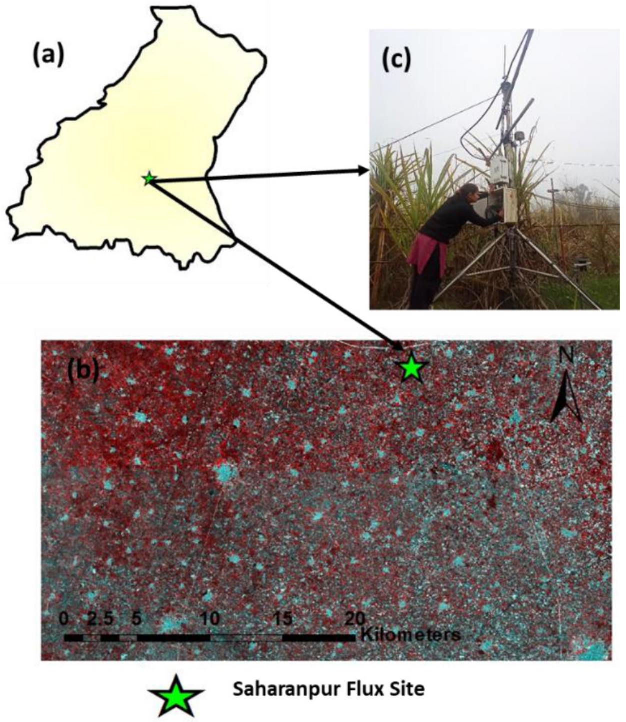

Fig 1: Location of the study site, a) Saharanpur map b) Location of the site on the false colour composite image of Sentinel 2 c) represent photograph of eddy covariance flux tower mounted within sugarcane crop at Saharanpur

The carbon and water vapour fluxes were computed using the eddy covariance technique, with the corresponding equations listed in Table 1. In addition to the flux dataset, meteorological variables were measured using the sensors installed at the flux tower site. These measurements were stored in data logger and collected for analysis. The raw dataset obtained from the EC tower underwent initial processing using Eddy Pro software to improve the data quality. The improved dataset is further processed to compute fluxes at various time scales. The details of the study sites, instrumentation along with flux data processing is detailed in Patel *et al*., (2021) and Pokhariyal *et al*., (2021). The variables used in the present study are tabulated in Table 1. Gc was calculated based on Penman Monteith's equation (Monteith, 1965) (Eq. 1) using the EC data:

$$\mathrm{Gc} = \frac{\Upsilon * \mathrm{LE} * \mathrm{Ga}}{\Delta(\mathrm{QR}-\mathrm{QG}) + \rho * \mathrm{Cp} * \mathrm{VPD} * \mathrm{Ga} - \mathrm{LE}\,(\Delta+\Upsilon)} \tag{1}$$

where Δ(Pa K^{-1}) is the slope of saturated vapor pressure against temperature, QR and QG (Wm-2) are the net radiation and ground heat flux, ρ (kg m^{-3}) is air density, C_p (J kg^{-1} K^{-1}) is specific heat of air, (Pa K^{-1}) is the psychrometric constant, VPD (Pa) is vapor pressure deficit, LE (W m^{-2}) is latent heat flux, and Ga (m s^{-1}) is aerodynamic conductance, calculated using the Monteith–Unsworth model (Monteith and Unsworth 1990) as depicted through Eq. 2.

$$\mathrm{Ga} = ((u/u*^{2}) + 6.2u*^{-2/3})^{-1} \tag{2}$$

u (m s^{-1}) is wind speed, and $u*$ is the friction velocity (m s^{-1}).

Statistical analysis

We analysed maximum temperature (T_{max}) data from EC flux site of March, April and May (MAM) month for the year 2014 to 2022 for heat wave characterization over the study site. Anomaly and z-scores value was calculated to evaluate the heat and non-heat events during the relevant study period. Anomaly simply represent the difference between present observation and mean of previous observations. The z-score depict the number of standard deviations (σ) an observation is above or below the mean.

$$\text{Anomaly} = T_{max}\ (2022) - \text{Average}\ (T_{max}\ (2014{:}2021)) \tag{3}$$

Table 1: Datasets used in the present study

Variable	Abbreviation	Unit	Source	Spatial coverage	*Temporal* coverage	***Equations***
Net ecosystem exchange	NEE	µ mol m^{-2} s^{-1}	EC tower	Point based	Daily	
Latent heat flux	LE	Wm^{-2}	EC tower	Point based	Daily	
Sensible heat flux	H	Wm^{-2}	EC tower	Point based	Daily	
Atmospheric carbon dioxide	CO_2	ppm	EC tower	Point based	Daily	-
Temperature	Tmax, Tmin	°C	EC tower	Point based	Daily	-
Vapour pressure deficit	VPD	kPa	EC tower	Point based	Daily	-
Stomatal conductance	Gc	$m\ s^{-1}$	EC tower	Point based (Eq. 1)	Daily	Eq. 1, Eq.2
Land surface temperature	LST	°C	Satellite (MOD11A1, MYD11A1)	1000 m	8 days	-

- latent heat of vaporization (J mmol water-1), - density of air (g m^{-3}), - Specific heat capacity of air at constant pressure (J g^{-1} K^{-1}), - indicate CO_2 density (mmol m^{-3}),- temperature (°C), - vertical wind velocity (m s^{-1}),- H_2O density (mmol m^{-3})

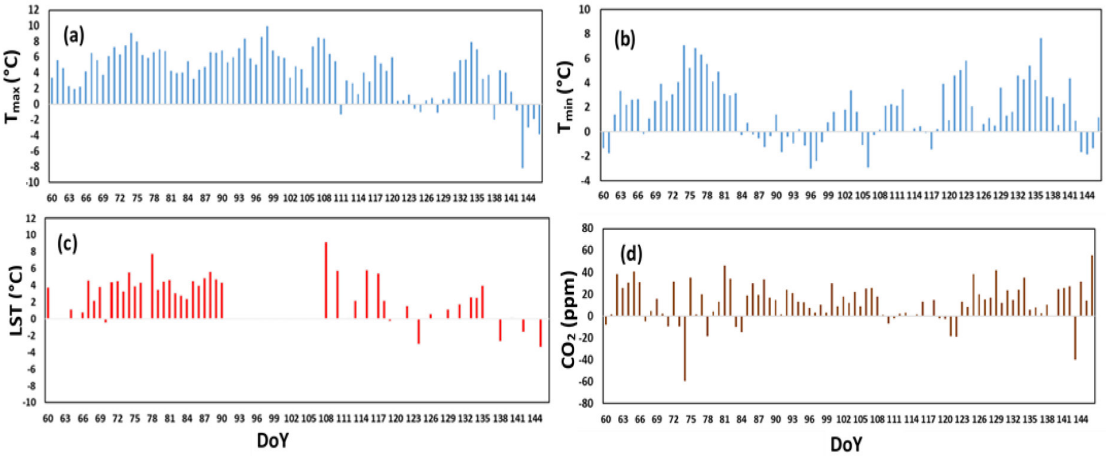

Fig 2: Anomaly of a) maximum temperature (T_{max}, °C), b) minimum temperature (T_{min}, °C), c) land surface temperature (LST, °C) and d) atmospheric CO_2 concentration (CO_2, ppm) throughout the study period

$$Z\text{–score}=(T_{max}(2022)\text{-Average}(T_{max}(2014{:}2021)))/\sigma\,(2014{:}2021) \quad (4)$$

In the year 2022, heat events were characterized when anomaly and z-score value exceed from 5°C and +2 σ, respectively for 6 consecutive days (Mandal *et al.*, 2019). Based on this criterion, the study period was characterized into two heat wave events (HE1 and HE2) and one non-heat wave event (NHE). Similarly, anomaly is also calculated for minimum temperature (T_{min}), atmospheric carbon dioxide concentration (CO_2), day-time LST using Eq. 1. We also compared the diurnal variation in NEE, LE, H, VPD, Gc, Bowen ratio (BR) and Ta of MAM for the year 2020 and 2022 during both heat and non-heat wave events. In the year 2020 and 2022, ratooned sugarcane crop was grown in the study area, representing similar crop type for synchronised comparison.

RESULTS AND DISCUSSION

Characterization of heat wave

The first heat wave event (HE1) occurred from 13th to 21st March 2022, with a z-score value of above 2 σ and an anomaly above 5°C. The second heat wave event, meeting the similar criteria, took place from 29th March to 11th April 2022 while non heat wave event defined from 1st May to 31st May. In SFS, the maximum temperature attained the peak of 41.21°C with a VPD of up to 6.7 kPa. In HE1, the T_{max} anomaly ranged from +5.9°C to +9.1°C, while in HE2, it ranged from +5°C to +9.9°C (Fig. 2). The T_{min} anomaly was found positive only during HE1, and it ranged from +5.2°C to +7.7°C. The recent reports on heatwaves by the Indian Council of Agricultural Research (Bal *et al.*, 2022) highlighted significant deviations in weekly maximum and minimum temperature across 6 regions in Central and Northern India from February to May. The authors found that Ludhiana experienced a deviation of +5.6°C, Kanpur +3°C, Samastipur 2.4°C, Jabalpur +3.7°C, and Raipur +3°C compared to the normal temperatures (1991-2020). Additionally, apart from being the hottest year in 2022, the period from February to May exhibited notably drier conditions in many regions. LST anomaly derived from MODIS datasets was positive in March and April but negative in May, aligning with the T_{max} anomaly trend as

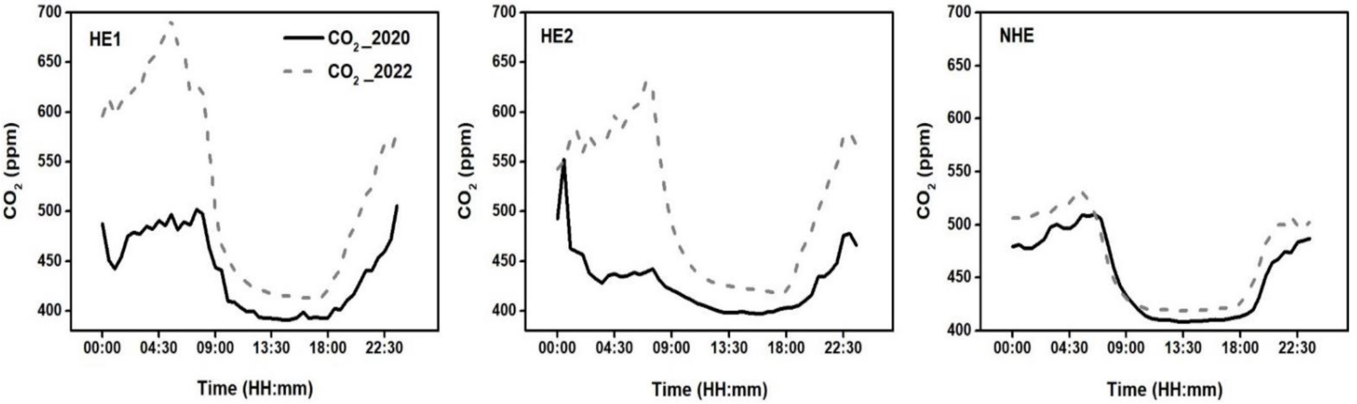

Fig 3: Variation in atmospheric CO$_2$ concentration in sugarcane during HE1, HE2 and NHE in 2020 and 2022

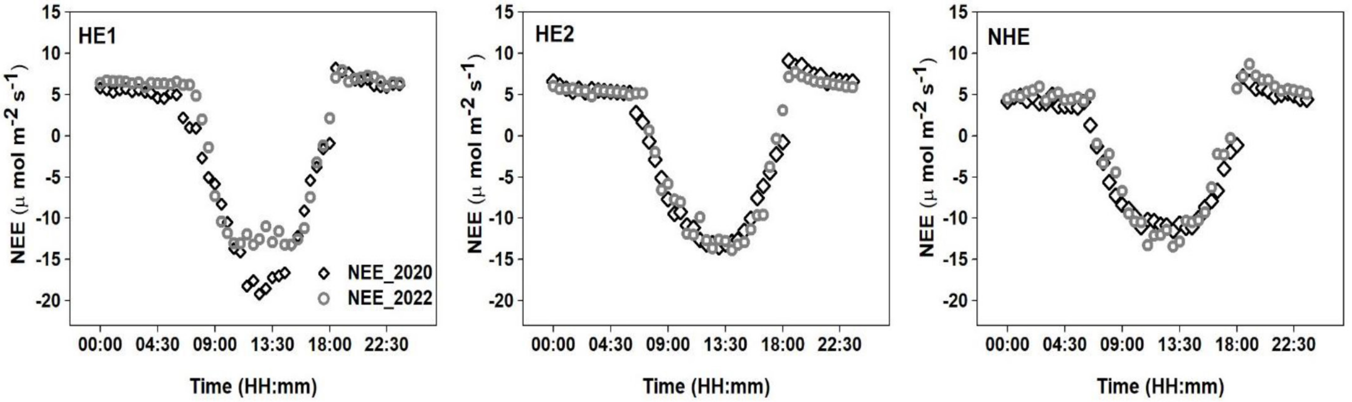

Fig 4: Variation in net ecosystem exchange (NEE, μ mol m^{-2} s^{-1}) during HE1, HE2 and NHE in 2020 and 2022 of sugarcane

illustrated in Fig. 2. These trends indicate heat wave events primarily occurring in March and April.

Effect of heat wave on atmospheric CO$_2$ concentration in sugarcane

Carbon concentration anomaly during the study period was found positive (80%), reaching up to 46.2 ppm (Fig. 2d). This indicates that the CO$_2$ concentration in 2022 was significantly higher than the average observed concentration from 2014 to 2021. Diurnal variation in the atmospheric CO$_2$ concentration was evaluated for the three heat wave events in 2020 and 2022 (Fig. 3). CO$_2$ concentration was higher in 2022 compared to 2020, with a similar trend for HE1 and HE2. In HE1, the night-time CO$_2$ concentration difference than during the daytime, exceeding that observed in HE2. Night-time CO$_2$ concentration difference was 189 ppm in HE1 and 79 ppm in HE2, while daytime difference was 21.93 ppm in HE1 and 19.12 ppm in HE2. During NHE, the daytime and night-time CO$_2$ concentration differences ranged from 9.9 ppm to 21.47 ppm. Tiwari *et al*., (2014) and Gupta *et al*., (2021) also reported increase in CO$_2$ concentration with higher surface temperatures.

Effect of heat wave on carbon and water vapour fluxes in sugarcane

The diurnal variation of NEE was also assessed during the three heat wave events (Fig. 4). As expected, NEE was negative during the day-time and positive during the night-time. In HE1, maximum NEE in the year 2020 and 2022 was -19.15 μ mol m^{-2} s^{-1} and -13.21 μ mol m^{-2} s^{-1}, respectively. NEE in 2022 was reduced by 5.94 μ mol m^{-2} s^{-1} compared to 2020. In HE1, before sunrise NEE was higher in year 2022 than in the year 2020 by 0.33 μ mol m^{-2} s^{-1}. The difference was not found prominent in both HE2 and NHE. The number of hours during which the ecosystem was sequestering carbon was reduced from 10.5 h in 2020 to 9.5 h in 2022 during both HE1 and HE2. During NHE, the ecosystem started to recover, with a difference of only 0.5 h in the number of hours for carbon sequestration. NEE also increased in 2022 during NHE by 1.37 μ mol m^{-2} s^{-1}. Gupta *et al*., (2021) also reported decrease in NEE in forest and agricultural ecosystems owing to higher temperatures. Heat waves also has increased respiration due to the exponential relationship between temperature and respiration (Frank *et al*., 2015)

The water vapour fluxes followed a similar pattern to the NEE (Fig. 5). LE increased throughout the study as sugarcane growth development in the area. The maximum LE values were 289.33 Wm^{-2} (2020) and 280.51 Wm^{-2} (2022), 356.08 Wm^{-2} (2020) and 338.79 Wm^{-2} (2022), 321.5 Wm^{-2} (2020) and 325.31 Wm^{-2} (2022) during HE1, HE2 and NHE, respectively. The LE was higher in 2020 for HE1 and HE2, but lower than 2022 for NHE. Similarly, the maximum H values were 266. 17 Wm^{-2} (2020) and 189.87 Wm^{-2} (2022), 282.71 Wm^{-2} (2020) and 119.87 Wm^{-2} (2022), 103.5

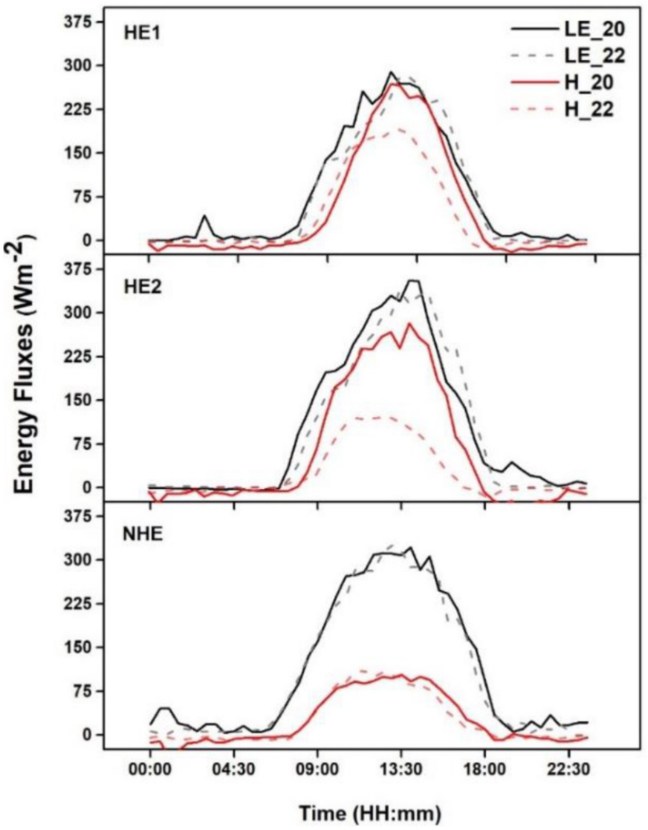

Fig 5: Variation in latent heat flux (LE, Wm^{-2}) and sensible heat flux (H, Wm^{-2}) in sugarcane during HE1, HE2 and NHE in 2020 and 2022.

Wm^{-2} (2020) and 109.65 Wm^{-2} (2022) during HE1, HE2 and NHE, respectively. In 2020, the available energy was more or less equally directed towards sensible and latent heat flux during HE1 and HE2, while during NHE, the LE was higher than H by 63.30 Wm^{-2}. On the other hand, in 2022, more available energy was directed towards LE throughout the study period, with the largest difference during NHE, where LE was higher than H by 146.19 Wm^{-2}. H values were higher in 2020 compared to 2022 during both HE1 and HE2. H remained relatively similar during NHE in both years.

Effect of heat wave on meteorological variables

The diurnal variation in average temperature (T_{avg}) was evaluated during 3 heat wave events (Fig. 6a). Diurnal Tavg was higher in 2022 compared to 2020 throughout the study period. The difference in Tavg was higher during HE1 and HE2 compared to NHE. The increase in Tavg during 2022 was higher in the afternoon than in the morning during HE1. Increase in Tavg values ranges from +3.24 °C to +8.12 °C in the year 2022 than in comparison to the year 2020. For HE2, Tavg remained relatively similar at 06:00 AM, but significantly increase after 10:00 AM. The difference in Tavg ranged from -0.26°C to +8.50°C. In 2020, a steady increase in Tavg (+1.62 °C to +3.83 °C) was observed during NHE. VPD in 2022 was highest during 2022 than in 2020 throughout the study period (Fig. 6b). Among the assigned heat waves and non-heat wave events, VPD was highest during HE2, followed by HE1 and NHE. Maximum VPD was recorded during the afternoon hours, reaching 3.26 k Pa (2022) and 1.60 k Pa (2020) for HE1, 5.20 k Pa (2022) and 1.88 k Pa (2020) for HE2 and 4.05 k Pa (2022) and 2.72 kPa (2020) for NHE. The range of difference in VPD from morning to evening hours was also higher during HE2 (+0.21 k Pa to +3.40 k Pa), followed by HE1 (+0.24 k Pa to +1.75 k Pa) and NHE (-0.09 k Pa to +1.33 k Pa).

Effect of heat wave on physiological variable in sugarcane

The variation in Gc was also evaluated during the 3 heat wave events (Fig. 7). Gc was lower in 2022 compared to 2020 throughout the study period. The variation in Gc was discernible from 06:00 hr to 18:00 hr. The maximum Gc values were 0.017 ms^{-1} (2020) and 0.009 ms^{-1} (2022), 0.014 ms^{-1} (2020) and 0.006 ms^{-1} (2022), 0.014 ms^{-1} (2020) and 0.007 ms^{-1} (2022) during HE1, HE2 and NHE, respectively. The difference in Gc between both the years was highest during HE1 ranging from -0.0002 ms^{-1} to -0.01 ms^{-1}, while during HE2 and NHE the difference in Gc was found quite similar. Heat waves have prominent impact on photosynthesis (Frank *et al.,* 2015). Plant regulates stomata to balance the risks of carbon starvation and hydrologic failure during heat waves (Choat *et al*., 2012). Plant stress occurs due to high temperatures and increased evaporative demand (high VPD) during heat waves (Gorsel *et al*., 2016), as observed in our study (5.20 k Pa during HE2). Subsequently, drought stress occur when soil water is not sufficient to meet the plant evaporative demand. The combination of high temperature, VPD and limited water availability can reduce Gc, directly affecting carbon uptake by the plant (Frank *et al*., 2015). Decreased Gc (more than 50% difference in Gc during HE2) also led to increase in the canopy temperature further affecting carbon sequestration by crops.

In sugarcane crop, heat stress can greatly change the physiological processes, leading to suppressed growth and yield (Wahid *et al*., 2007). Gomathi *et al.,* (2013) reported the impact of higher temperature on the smaller internodes and early drying of the leaves with reduced biomass in sugarcane. The chlorophyll content, relative water content and leaf gas exchange parameters of sugarcane tend to decrease under heat stress conditions (Kohila and Gomathi, 2018) as observed in our site in terms of NEE. Heat stress also causes abiotic disorder like sunburn in sugarcane during initial and mid-season crop establishment that could led to yield reduction in sugarcane by affecting its physiology, biochemistry and quality leading to poor agronomic produce. Morales *et al.,* (2003) reported reduction in the amount of photosynthetic pigments under heat stress in sugarcane. Similarly, Srivastava *et al*., (2012) reported reduction in net assimilation rate and relative growth rate under high temperature. Weather and climate related events are the prime factor for sugarcane production. Thus, climate change can significantly impact the sugarcane production. High temperature due to climate change in Brazil increases the evapotranspiration in sugarcane thus reducing soil water availability, thus considerably increasing irrigation demand (de Carvalho *et al*., 2015). Under doubled CO2, sugarcane yield is estimated to reduce by 20-40% in Southern Caribbean (Singh and Maayar, 1998). In India, Praveen *et al*., (2017) projected a decline in sugarcane yield in near, mid and end century period by 1.8%, 2.6% and 2.8%, respectively.

Limitations of the study

The lack of a long-term EC dataset is a limitation of the current study. The variation in fluxes was observed solely on data

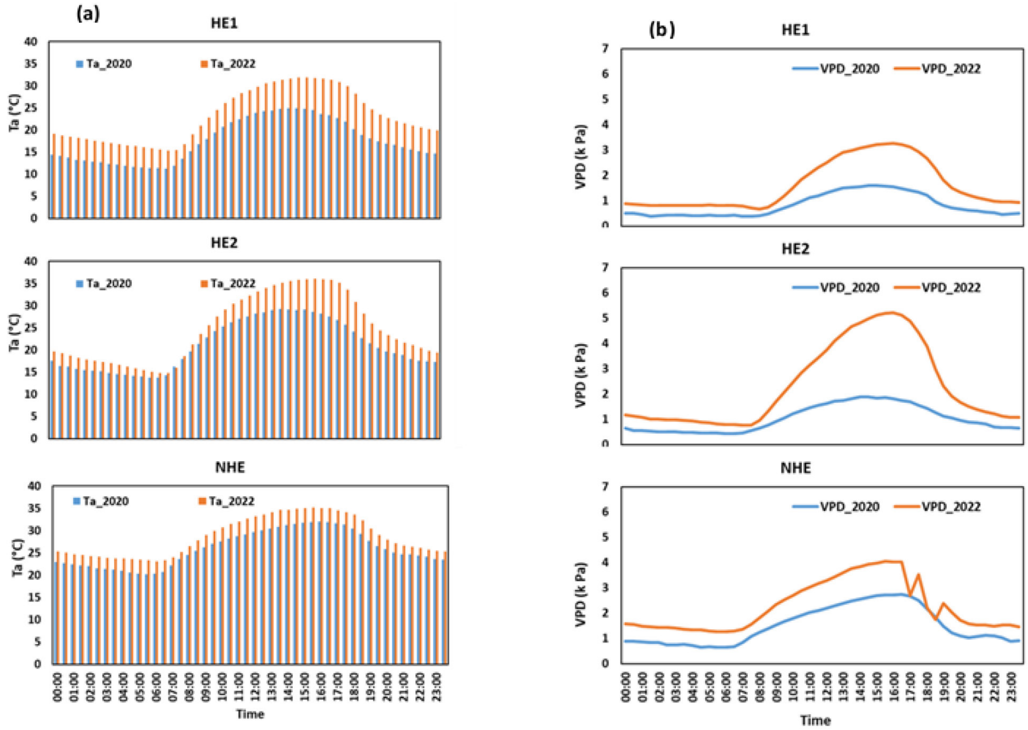

Fig 6: Variation in average temperature (a) and VPD (kPa) during HE1, HE2 and NHE in 2020 and 2022

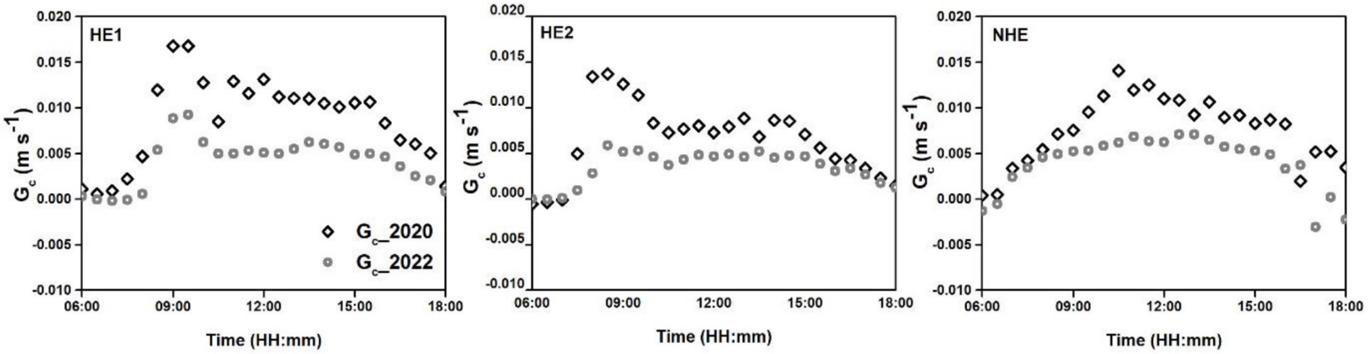

Fig 7: Variation in stomatal conductance during HE1, HE2 and NHE in 2020 and 2022

from the years 2020 and 2022. Furthermore, the study is focused only on sugarcane ecosystem, which can be enhanced in the future by incorporating long term EC datasets from various agroecosystems.

CONCLUSION

In the present study, carbon and energy fluxes are analysed during the heat wave period over sugarcane crop in India. NEE was reduced during the heat wave events in comparison to the non-heat wave event. Low carbon sequestration and high respiration due to increasing temperature lead to more CO_2 concentration in the atmosphere. In the similar way, water vapour fluxes were also affected. Latent heat flux (LE) was reduced by stomatal regulation during the heat wave event. High temperature and high evaporative demand stress the plants thus reducing the net carbon uptake by the plants, which could ultimately lead to reduction in crop yield. Recent reports estimated increase in duration, intensity or frequency of the heat wave in the near future, which can further exacerbate its impact on the crop performance further negating the efforts to improve the food security. In this regard, it is critical to improve the existing management strategies, and develop climate resilient crop varieties for sustainable food production under extreme weather event. The present study provides a unique reference for further climate change analysis, focusing on both carbon and energy fluxes over sugarcane, which holds a prominent position as a cash crop in India.

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Availability of data: Satellite data used is available in google earth engine. Eddy covariance data can be made available partially with reasonable agreement and request to the corresponding author.

Conflict of Interests: The authors declare that there is no conflict of interest related to this article.

Authors contribution: **S. Pokhariyal**: Data collection, Data Analysis, Conceptualization, Methodology, Visualization, Writing-original draft, Writing-review, **N.R. Patel**: Resources, Conceptualization, Methodology, Supervision, Writing-review and editing, **A. Danodia**: Data collection, Writing-review, **R.P. Singh**: Resources, Writing-review

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