Journal of Agrometeorology 21 (2) : 123-130 (June 2019)

Modeling impacts of climate change on spring wheat in northern India

SARITA KUMARI[1], S. BAIDYA ROY[1], P. SHARMA[2], A. SRIVASTAVA[1], V.K. SEHGAL[3] and R. DHAKAR[3]

[1]*Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi*
[2]*Department of Atmospheric Sciences, University of Illinois, Urbana, IL, USA*
[3]*Division of Agricultural Physics, Indian Agriculture Research Institute, Pusa Campus, New Delhi*
Corresponding author Email: *drsbr@iitd.ac.in*

ABSTRACT

This study attempts to quantitatively understand the impact of changes in meteorological drivers due to climate change on spring wheat in northern India using numerical experiments with the Simple and Universal CRop growth Simulator (SUCROS) model.The model was calibrated and evaluated for spring wheat cultivar HD2967 using observed crop and meteorological data from a field site at the Indian Agricultural Research Institute, New Delhi. Sensitivity studies were performed with the SUCROS model by incrementally changing the meteorological drivers to understand the underlying processes through which each meteorological driver affects spring wheat crop growth. The effect of climate change on spring wheat growth was estimated by conducting numerical experiments where the SUCROS model was driven with bias-corrected projections of future climate from six climate models for two scenarios for mid and end century. Results show that competitive/synergistic interactions between meteorological drivers lead to a slight increase in growth at the beginning of the growing season, and a strong decrease of about 50 per cent during the later stage. Apart from improving our understanding of crop growth processes, this study has also policy implications for agriculture and food security in the context of climate change.

Keywords : Crop model, SUCROS, spring wheat, climate change, agriculture in India

Spring wheat is the second major food crop in India that plays a critical role in meeting the food demand for the growing population of India. Hence, it is important to understand the dynamics of wheat growth and the factors that influence productivity (Zacharias *et al.,* 2014). Changing weather and climate conditions have direct and indirect impacts on crop growth and production (Yadav *et al.,* 2015). Many studies have investigated the impacts of meteorological drivers on spring wheat growth and yield using observed meteorological data (Hundal and Kaur, 2007; Lunagaria *et al.,* 2012; Pradhan *et al.,* 2018; Yadav *et al.,* 2015; Zacharias *et al.,* 2014) and future climate projections from climate models (Chatrath *et al.,* 2007; Patel *et al.,* 2018; Pandey *et al.,* 2007; Zacharias *et al.,* 2014). These studies have looked at the impacts of temperature, radiation and water availability. In general, they show that spring wheat is negatively affected by increasing temperature, decreasing radiation and increasing water stress.

It is well known that the variation in crop productivity is not based only on a single weather parameter change, but it is based on the collaborative effect of all different meteorological variables (Kingra, 2016). However, most existing studies focus only on the individual effects of a few key meteorological variables. In this study, we attempted to fill this knowledge gap by quantitatively investigating the combined impact of changes in different meteorological variables (temperature, radiation, vapour pressure, wind speed and soil moisture)due to changing climate on spring wheat growth and yield using observed meteorological data as well as future climate projections. We conducted sensitivity studies to understand the biophysical processes that cause these impacts.

MATERIALS AND METHODS

Field data

Data on phenology, growth and leaf area index (LAI) at different growth stages and yield for spring wheat were collected from an experimental site located at the Indian Agricultural Research Institute (IARI) campus in New Delhi (Fig. 1a).The site is located at 28°40'N, 77°12'E in a subtropical, semi-arid region.Wheat cultivar HD2967 crop was sown with a spacing of 20 cm (row to row) x 5cm (plant to plant) giving a plant density of 25 plants per sq m. The crop was sown on November 20.The crop was grown with optimum nitrogen and five irrigations: 22, 43, 67, 85 and 105 days after sowing.

The crop LAI was measured once a week using the LAI-2000 plant canopy analyzer from Li-COR. On each date, at least five LAI observations were taken at different locations within the plot and averaged to obtain the representative LAI for that day. At the end of the growing season, two samples of mature wheat crop were harvested from a one square meter area in each plot and allowed to air dry. The grains were thrashed and winnowed by a mechanical thrasher and weighed to estimate grain yield. LAI data is available for 3 growing seasons: 2014-15, 2015-16 and 2016-17 while yield data is available for 2 years: 2015-16 and 2016-17. Meteorological data including, temperature, wind speed, incoming radiation and vapour pressure were also collected during the field experiment from an agrometeorological observatory located near the experimental plot.

Crop growth model: Description and calibration

The numerical simulations are conducted using the crop model Simple and Universal CRop growth Simulator version 2 (SUCROS, Goudriaan and Van Laar, 1994). This is a well-known model that has been used for many different applications. The model description and code is publicly available. The code was converted to FORTRAN90 from the native FST format. For brevity, only a brief description of the key features is provided here. SUCROS computes crop growth on the basis of various plant processes and environmental conditions. First, leaf CO_2 assimilation is calculated as a function of its maximum rate at light saturation, temperature effect, the effect of ageing and emergence of seedling. A part of assimilated carbon is used to maintain plant respiration and the remaining part is partitioned among roots, leaves and shoots (stem and storage organ) depending on the development stage of the plant. These processes are functions of the development stage and environmental factors including incoming radiation, ambient temperature, vapour pressure deficit, wind speed and soil moisture. The model simulations started on November 30, the approximate day of emergence, and continued with a 1-day time step till April 30 of the next year. The effect of irrigation was simulated by setting the soil moisture to 90 per cent of the field capacity on the days when irrigation was applied.

The SUCROS model was calibrated for spring wheat using LAI and yield data for 2015-16 and validated against data for 2014-15 and 2016-17. Calibration involved finding the optimum combination of various SUCROS coefficients that produces the best match with the observed LAI and yield. First, a literature survey was undertaken to collect the values of the coefficients. Multiple values were obtained for many coefficients. A UNIX script was devised to conduct SUCROS simulations with all possible combinations and calculate various performance metrics including, bias, mean absolute error and root mean square error. The simulations were ranked on the basis of the values of these performance metrics and the combination with the best average rank was selected. The selected combination was further fine tuned to obtain the final set of values (Table 1). This calibration process ensures that the parameter values are always within the range found in the literature and generates the most optimal match between observed and simulated values.

Climate projections

Climate projections are obtained from the Coupled Model Intercomparison Project 5 (CMIP5, Taylor *et al.,* 2012) dataset available online at https://cmip.llnl.gov/cmip5/. We used data from all the six General Circulation models (GCMs), viz., CNRM-CM5, GFDL-ESM2G, GFDL-ESM2M, MIROC5, MIROC-ESM and MIROC-ESM-CHEM, that provided daily projections of all meteorological variables, including soil moisture, that are required to run the SUCROS model. The following five different climate projections (Taylor *et al.,* 2012) were used in this study:

1. 2011-2020 RCP 8.5 as the baseline case
2. 2041-2050 RCP 2.6 as the mid-century low impact scenario
3. 2041-2050 RCP 8.5 as the mid-century high impact scenario
4. 2091-2100 RCP 2.6 as the end-century low impact scenario
5. 2091-2100 RCP 8.5 as the end-century high impact scenario.

Each of these scenarios was bias-corrected using observed meteorological data from the study site. The bias-corrected climate projections were used to drive the calibrated SUCROS model and conduct 30 10-year long simulations.

Simulation design

First, the SUCROS model was calibrated using daily mean temperature, vapour pressure, wind speed and total accumulated incoming radiation observed at the field site. The model was also initialized with observed soil moisture. Thereafter, sensitivity studies were conducted to understand the role of individual meteorological variables on spring

Table 1: Calibrated SUCROS coefficients for spring wheat

Parameter	Value
Initial Leaf Area Index	0.014 m^2 leaf m^{-2}
Potential CO_2 assimilation rate at light saturation	0.0021692 g CO_2 m^{-2} s^{-1}
Initial light conversion factor	13.0e-06 g CO_2 / J
Extinction coefficient	0.6 m^2 ground ha^{-1} leaf
Scattering coefficient of leaves for PAR	0.19
Maintenance respiration coefficient of leaves	0.015 CH_2O g^{-1} DM d^{-1}
Maintenance respiration coefficient of stems	0.005 CH_2O g^{-1} DM d^{-1}
Maintenance respiration coefficient of storage organ	0.01 CH_2O g^{-1} DM d^{-1}
Maintenance respiration coefficient of roots	0.015 CH_2O g^{-1} DM d^{-1}
Assimilate requirement for leaf dry matter production	1.5 g CH_2O g^{-1} DM leaf
Assimilate requirement for root dry matter production	1.544 g CH_2O g^{-1} DM root
Assimilate requirement for stem dry matter production	1.1 g CH_2O g^{-1} DM stem
Assimilate requirement for storage organ dry matter production	1.0 g CH_2O g^{-1} DM storage organs
Constant for root elongation	14 mm d^{-1}
Fraction stem weight eventually translocated to storage organs	0.35

Table 2: Changes in meteorological drivers used for sensitivity experiments to understand the impacts of each individual driver

Variables	Changes	Amount changed	No. of simulations
Incoming shortwave radiation	Increased	+10%, +20%, +30%, +40%, +50%	5
	Decreased	-10%, -20%, -30%, -40%, -50%	5
Daily average temperature	Increased	+1°C, +3°C, +5°C , +7°C	4
	Decreased	-1°C, -3°C, -5°C , -7°C	4
Daily average vapour pressure	Increased	+10%, +20%, +30%, +40%, +50%	5
	Decreased	-10%, -20%, -30%, -40%, -50%	5
Daily mean wind speed	Increased	+10%, +20%, +30%, +40%, +50%	5
	Decreased	-10%, -20%, -30%, -40%, -50%	5
Daily mean soil moisture	Increased	+0.05cm^3 H_2O cm^{-3} soil,+0.1cm^3 H_2O cm^{-3} soil	2
	Decreased	-0.05cm^3 H_2O cm^{-3} soil,-0.1cm^3 H_2O cm^{-3} soil	2

wheat growth. For this purpose, the meteorological factors are incrementally changed (Table 2) leading to 42 simulations.Finally, the aggregated effects of changes in multiple meteorological drivers due to climate change were studied by conducting 300 simulations driven by daily meteorological variable projections from climate models.

RESULTS AND DISCUSSION

Crop model calibration and validation

Results show that the calibrated crop model performs quite well in simulating the spring wheat phenology (Fig. 1). Calibration was done for year 2015-16 and validation for years 2014-15 and 2016-17. Simulated LAI values closely match the observed LAI for both evaluation years. The correlation coefficient between simulated and observed LAI is 0.9 significant at $p < 0.001$. The simulated mass of the storage organ also closely matches the final grain yield for the validation year 2016-17.

Sensitivity studies

The sensitivity studies allow us to quantitatively study the impact of each meteorological driver and unearth the underlying processes that determine the response of the crop to changing meteorological conditions. For brevity, only 20 selected results, 4 for each meteorological driver, are shown in Fig. 2. Results show that increasing incoming radiation increases LAI (Fig. 2a(i)) and yield (Fig. 2a(ii)) due

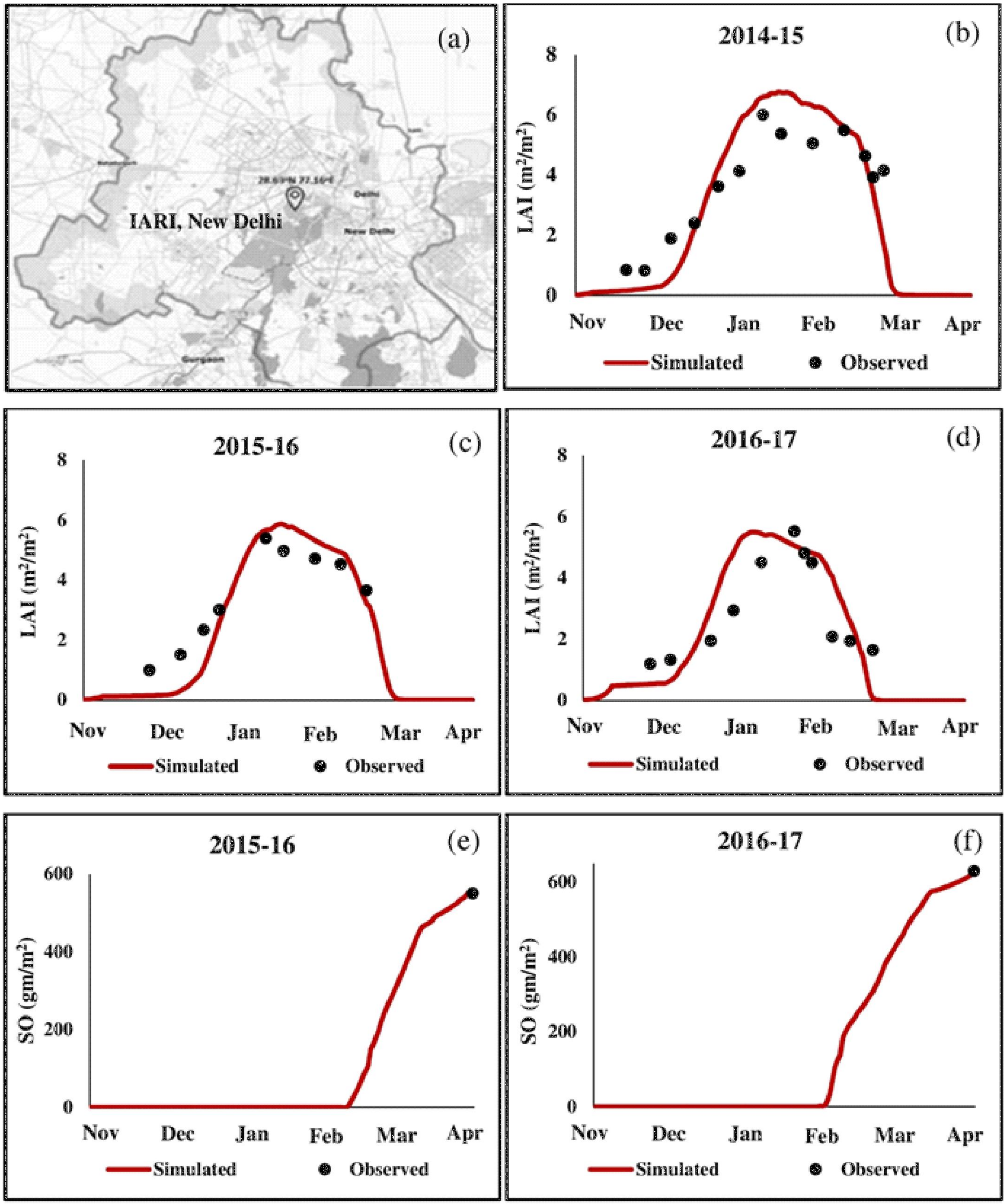

Fig. 1: (a) Study area; Observed and simulated LAI for (b) 2014-15, (c) 2015-16, and (d) 2016-17 spring wheat growing seasons; Observed yield (g m^{-2}) and simulated storage organ (g m^{-2}) for (e) 2015-16 and (f) 2016-17. The weight of the storage organ at the end of the growing season is the yield.

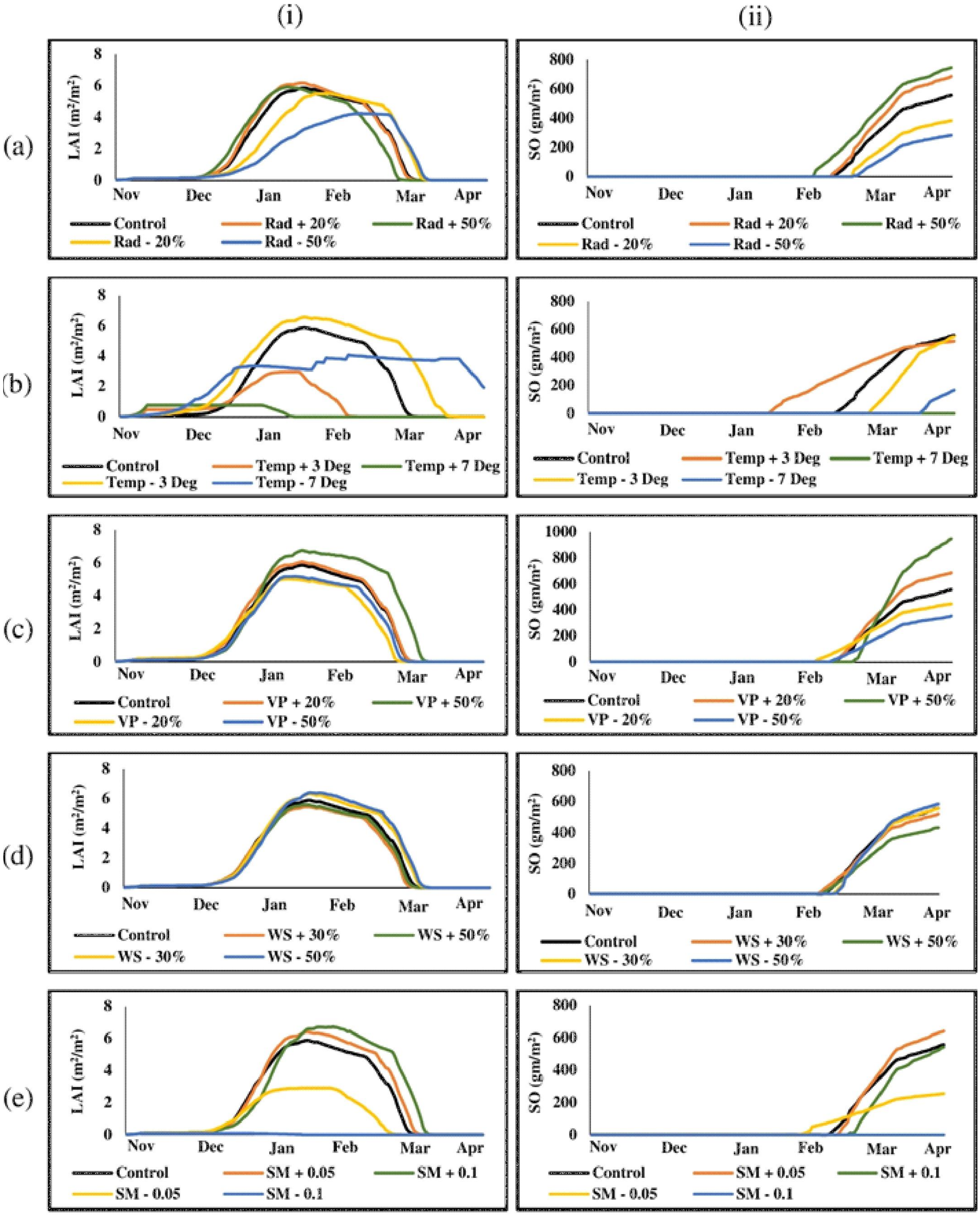

Fig. 2 : Sensitivity of (i) LAI and (ii) storage organ growth due to changes in (a) radiation, (b) temperature, (c) vapour pressure, (d) wind speed and (e) soil moisture at emergence

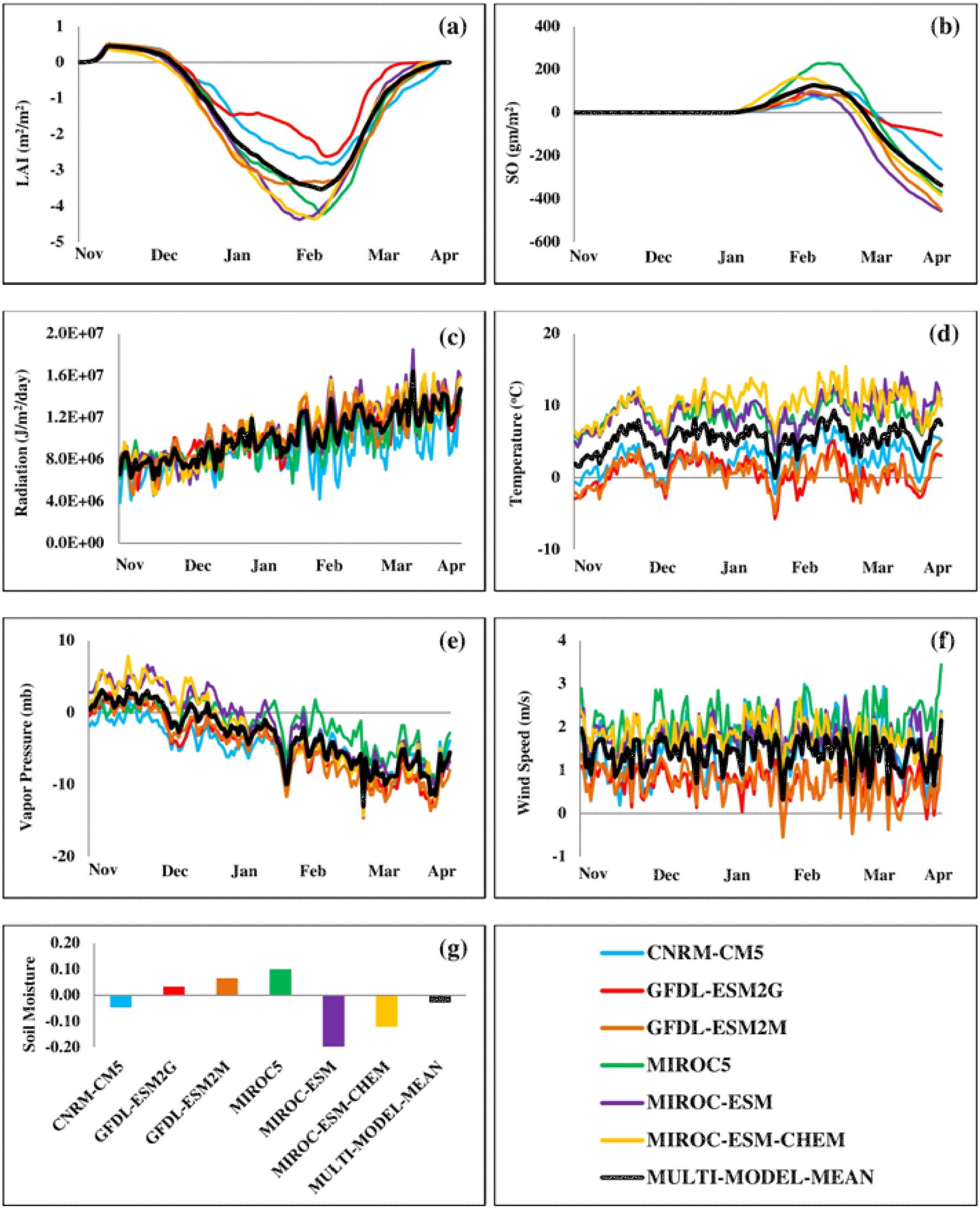

Fig. 3 : Anomaly from baseline for RCP 8.5 end-century case for (a) LAI, (b) storage organ, (c) incoming shortwave radiation, (d) temperature, (e) vapour pressure, (f) wind speed and (g) soil moisture of the topmost layer

to more photosynthesis. However, more radiation also leads to more evaporation and hence,less soil moisture availability, which reduces the croplife span, causing early senesence. Increased temperature increases plant respiration and soil evaporation,thereby reducing LAI growth rate (Fig. 2b(i)). With increased development rate due to increased temperature, the crop duration is also decreased. Decreased temperature means less respiration and also less soil evaporation that reduces water stress. It also increases the crop duration due to reduced development rate. But after a threshold temperature, decrease in temperature results in reduced growth and reduced yield as depicted in Fig. 2b(ii). When thevapour pressure increases, the risk of drying is low;hence, plants can keep the stomata open,which increases CO_2 uptake, resulting in increased LAI and increased yield (Fig. 2c). Under low vapour pressure, the plants resist opening their stomata to preserve water; so less CO_2 is taken up, reducing plant growth and yield. Increased wind speed enhances the drying power of plant that results in higher evapotranspiration, which may increase water stress if soil moisture supply is inadequate. This decreases LAI and storage organ[Fig 2d(i) and (ii)].The crop is irrigated, so the effect of water stress is likely to be low. However, irrigation occurs almost 10 days after emergence and hence the soil moisture at the time of emergence is a critical factor. Increasing the soil moisture at emergence reduces water stress and enhances LAI and storage organ growth while reduction in soil moisture leads to lower LAI and yield. If the soil moisture is reduced by 0.1 cm^3 H_2O cm^{-3} soil, the crop does not grow at all (Fig. 2e).

Impact of climate change

The impact of changing meteorological drivers due to climate change is studied using two different scenarios viz., RCP 2.6 and RCP 8.5 for mid-century (2041-2050) and end-century (2091-2100) by considering (2011-2020) as a baseline. Crop growth and productivity are reduced in both scenarios and both time periods. For brevity, we only present the results from the end-century RCP 8.5 scenario where the effects of changing meteorological conditions are the strongest. Fig. 3 shows the projected anomalies (baseline-future scenario) in spring wheat growth and meteorological drivers for end-century RCP 8.5 case for all 6 GCMs. Each projection is an average of 10 years simulations using that GCM. Because all GCM projections show similar patterns, we confine our analysis to the multi-model mean.

Results show that the multi-model mean LAI (Fig. 3a) and storage organ (Fig. 3b) anomaly are strongly negative later leading to almost 50 per cent decrease in LAI and yield over baseline values.During the simulation period, the incoming radiation (Fig. 3c), temperature (Fig. 3d) and wind speed (Fig. 3f) are much higher than the baseline;vapour pressure (Fig. 3e) is slightly higher at the beginning of the growing season but much lower thereafter; and the soil moisture at emergence is slightly lower than the baseline.

The dominant factor behind the reduction in growth is increase in water stress due to increased evapotranspiration caused by lower vapour pressure, higher radiation, temperature and wind speed. Moreover, the increased temperature also increases the respiratory losses leading to a reduction in net carbon assimilation. Increased temperature also shortens the phenology in general and grain filling duration in particular, resulting in less time for carbohydrates to translocate to grains.

Interestingly, the results also show a slight increase in growth at the beginning of the growing season. This increaseis likely due to the high vapour pressure (Fig. 3e) at the beginning of the season that allows the plant to keep their stomata open for longer periods and thus absorb more carbon. This is aided by an increase in temperature (Fig. 3d) that increases the development and carbon assimilation rates and the increase in incoming radiation (Fig. 3c) that enhances photosynthesis rates. Some of this growth is offset by the increase in wind speed (Fig. 3f) that can increase evapotranspiration and a slight reduction in initial soil moisture (Fig. 3g) both of which can increase the water stress on the plants during emergence.

CONCLUSIONS

This study attempted to quantitatively understand the impact of changes in meteorological drivers due to climate change on spring wheat in northern India using the SUCROS model, observed LAI, yield and meteorological data from a field site and future climate projections from 6 CMIP5 GCMs. The key conclusions of the study are:

- The calibrated SUCROS model is able to capture the observed crop growth dynamics over the IARI field site.
- Spring wheat growth is strongly influenced by meteorological factors that act by affecting the development rate, photosynthesis, carbon assimilation, and water stress. The sensitivity studies are able to identify the processes through which each meteorological factor affects spring wheat growth.
- Simulations show that changes in meteorological drivers

due to climate change can lead to a strong decrease in spring wheat growth. In the most extreme RCP 8.5 end-century scenario, the multi-model mean peak LAI and yield show a reduction of about 50 per cent. This strong reduction is mainly due to (i) increased evapotranspiration caused by reduction in vapour pressure that increases the water stress and (i) increased temperature increases respiratory losses leading to a reduction in net carbon assimilation and also shortens the phenology.

The current study looks only at meteorological drivers that act as biogeophysical controls on crop growth. Biogeochemical controls such as increase in atmospheric carbon concentration and nutrient availability due to fertilizer applications are likely to play a very strong role. These factors are being considered in an ongoing study.

ACKNOWLEDGEMENTS

This work was funded by the Science and Engineering Research Board, Department of Science and Technology, Govt. of India, Grant number SB/S4/AS-146/2014.

REFERENCES

Chatrath, R., Mishra, B., Ortiz-Ferrara, G., Singh, S.K. and Joshi, A.K. (2007). Challenges to wheat production in South Asia. *Euphytica.*, 157: 447–456.

Goudriaan, J. and Van Laar. H. H. (1994) Modelling Potential Crop Growth Processes, 2nd ed, Kluwer, Dordrecht, Netherlands.

Hundal, S. S. and Kaur P. (2007). Climate variability and its impact on cereal productivity in Indian Punjab. *Cur. Sci.*, 92(4): 506-512.

Kingra, P. K. (2016). Climate variability impacts on wheat productivity in central Punjab. *J. Agrometeorol.*, 18(1): 97-99.

Lunagaria, M.M., Pandey, V. and Patel, H.R. (2012). Climatic trends in Gujarat and its likely impact on different crops. *J. Agrometeorol.*,14(1): 41-44.

Pandey, V., Patel H.R. and Patel, V.J. (2007). Impact assessment of climate change on wheat yield in Gujarat using CERES-wheat model. *J. Agrometeorol.*, 9(2):149-157.

Patel, C., Nema, A.K., Singh, R.S., Yadav, M.K., Singh, K.K., Singh, S.K., Rai, P.K. and Singh, S.M. (2018). Assessment of climate change impact on wheat crop using MarkSim GCM in Varanasi, Uttar Pradesh. *J. Agrometeorol.*, 20(3): 216-218.

Pradhan, S., Sehgal, V.K., Sahoo, R.N., Bandyopadhyay, K.K. and Singh, R. (2018). Yield, water and radiation use efficiency of wheat as influenced by irrigation levels in a semiarid environment. *J. Agrometeorol.*, 20 (SP-I): 31-36.

Taylor, K.E., Stouffer, R. J. and Meehl, G.A. (2012) An Overview of CMIP5 and the experiment design, Bull. *Amer. Meteor. Soc.*, 93:485-498.

Yadav, M.K., Singh, R.S., Singh, K.K., Mall, R.K., Patel, C.B., Yadav S.K. and Singh M.K. (2015). Assessment of climate change impact on productivity of different cereal crops in Varanasi, India. *J. Agrometeorol.*, 17(2): 179-184.

Zacharias, M., Naresh Kumar, S., Singh, S.D., Swaroopa Rani, D.N. and Aggarwal, P.K. (2014). Assessment of impacts of climate change on rice and wheat in the Indo- Gangetic plains. *J. Agrometeorol.*, 16(1): 9-17.

Received : January 2019 ; Accepted : May 2019