Parametrization of the DO_3SE stomatal flux model for five Indian winter wheat cultivars

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A dissertation submitted for the partial fulfilment of BS-MS dual degree in Science

Indian Institute of Science Education and Research Mohali
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Certificate of Examination

This is to certify that the dissertation titled "Parametrization of the DO3SE stomatal flux model for five Indian winter wheat cultivars" submitted by Mr. Sukhwinder (Reg. No. MS13082) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. B. Sinha (Supervisor)	Dr. V. Sinha	Dr. P. Balanarayan

Dated: November 28, 2018

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Baerbel Sinha at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Sukhwinder Singh
(Candidate)

Dated: November 29th, 2018

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Baerbel Sinha

(Supervisor)

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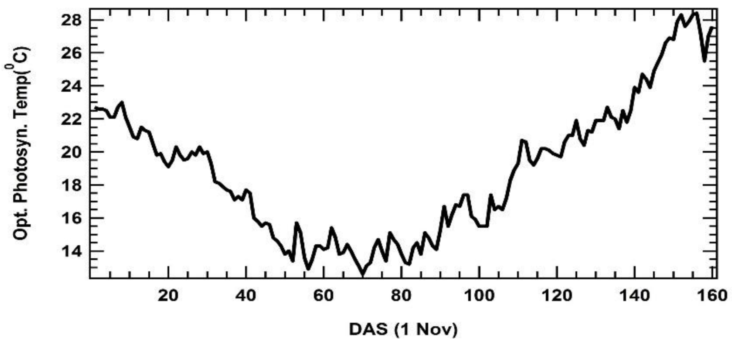

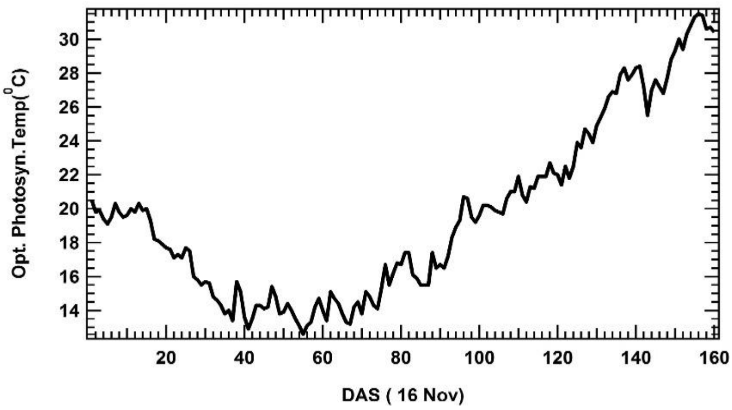

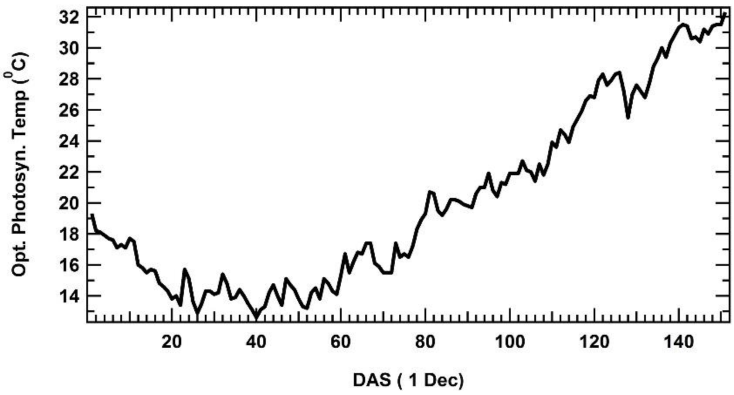

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Notation (Abbreviations)

AOT40 Accumulated Ozone exposure over a Threshold of 40 ppb.

DO_3SE Deposition of Ozone for stomatal exchange (model)

g_{sto} Stomatal conductance.

POD_Y Phytotoxic ozone dose above a thresh hold of Y.

SM Soil moisture.

VPD Vapour pressure deficit.

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Abstract

Measurements of leaf-level stomatal conductance (gsto) are central to the ozone (O3) risk assessment and the calculation of *Triticum aestivum* yield loss based on the absorbed O3 phytotoxic dose (POD).

In this study we present measurements and a comparative analysis of g_{sto} field measurements from four *triticum aestivum* cultivars grown as irrigated winter wheat in the state of Punjab, in the NW-IGP during winter 2016-17 and 2017-18. The cultivars RAJ3765, GW322, C306 and DBW88 were directly obtained from breeders, while local farmers cultivars obtained from a seed shop were grown for comparison.

The g_{sto} measurements in combination with phenology observations on the plants are used to derive environmental response functions for the parameters light, temperature, soil moisture, water vapour pressure deficit, plant phenology and time of the day for all nine *triticum aestivum* cultivars.

The response functions thus obtained can be used for two purposes. Firstly, we use them for revising the g_{sto} model parameterization of the DO3SE model in order to precisely model the ozone related crop yield losses using the POD_6 exposure-response functions for each of the cultivars for both growing seasons. Secondly, the same environmental response functions have also more immediate uses in identifying a given cultivars potential to cope well with certain climate change or air pollution related stressors, such as heat waves and droughts or its potential to fare well in years affected by prolonged wintertime fog in the NW-IGP.

Chapter 1

Introduction

1.1 Tropospheric ozone as an air pollutant

Troposphere ozone a secondary air pollutant. The precursor of ozone are NOx and VOCs (volatile organic compounds). The production of ozone is dependent on the level of NOx. In the rural areas level of NOx increases with burning of crop residue. It has its negative effect on human health, crops and native plants and decreases the net primary productivity. (Annu. Rev. Plant Biol. 2012.63:637-661.)

1.2 Effect of environmental factors on the stomatal flux of Ozone

The environmental factors and plant phenology play crucial role for regulating the stomata. (Mills et al., 2011b) showed that the effect of ozone on vegetation directly linked to the stomatal flux of O_3 than the ozone exposure.

DO_3SE model has developed to study the stomatal response to these environmental factors. (Büker et al., 2012; Emberson et al., 2000a,b, 2001, 2007). With using of this model Phytotoxic Ozone Deposition (POD) can be known.

There are two types of stomatal flux based critical level metrics:

1. POD_YSPEC (species or group of species specific)
2. POD_YIAM (vegetation type specific for large scale analysis)

1.3 Assessment of Stomatal Ozone flux

1.3.1 Calculation of hourly stomatal conductance of O3

Stomatal conductance(G_{sto}) multiplicative algorithm considered in DO_3SE model proposed by Jarvis (2016) and modified by (Emberson et al. (2000a, b)) has following formulation for G_{sto} max:

$$g_{sto} = g_{max} * \min\{(f_{phen}, f_{O3})\} * f_{light} * \max\{f_{min}, (f_{temp} * f_{VPD} * f_{SW})\}$$

Where, g_{sto} stands for the stomatal conductance (mmol O_3 m^{-2} s^{-1}) and g_{max} represents the maximum stomatal conductance of the speices.

These parameters (f_{phen}, $f_{O3,}$ $f_{light,}$ f_{min}, f_{temp}, $f_{VPD,}$ f_{SW}) represents their influence on stomatal conductance.

f_{phen}: Phenology of the plants is affected by the different environmental factors such as temperature, daylight-hours and precipitation etc. Phenology has a major role in the variation of the stomatal conductance. This function is maximum during the anthesis period. Plants life cycle icludes different growth phases starting from juvenile, vegetative and finally reproductive phase. These phages alter the plant physiology as result in the change of stomatal conductane.

f_{light}: Light plays crucial role in monitoring the phenology of the plants through photosynthesis. Stomatal conductance changes with the change in photon flux density (PFD) represents in mol $m^{-2}s^{-1}$. Stomatal conductance increases with the changes in the intensity of PFD up to a threshold and then decrease afterward.

f_{temp}: T_{min} is the minimum temperature before this plant keeps their stomata closed, T_{opt} is the temperature where the stomata are maximum open, and the maximum stomatal conductance observe. At T_{max} plants keeps stomata shut. Opening the stomata under high temperature induce the loss of water and opening stomata under low temperature prone to fungal infection to plants.

f_{VPD}: VPD is the vapour pressure deficit. It is the measure of dryness/humidity in the air. At the VPD_{max} the stomatal conductance is maximum and at VPD_{min} plants close their stomata i.e under drought conditions which are unfavourable for the growth.

f_{SW}: The soil water potential has no used for the parameterisation of POD_YIAM. But this is an important factor to look at. At a point where SWP is maximum the stomatal conductance is also high and at the minimum value of SWP the conductance decreases to minimum.

fO_3: This parameter is used for accounting the effect of ozone on promoting premature senescence (Pleijel et al. 2002).

1.3.2 Modelling hourly stomatal flux of O_3:

The stomatal conductance is not only the factor for quanyify the effect of ozone on vegetation, it is also important to know the ozone concentration above the canopy height the available concentartion present for the plant uptake (Emberson et al., 2000). The assumption in the formulation is that the ozone concentration at the top of canopy is same as the concentartion above leaf surface. The formulation for the calculation is given below:

$$F_{st} = c(z_1) * (1 / r_b + r_c) * (g_{sto} / g_{sto} + g_{ext})$$

where 'r_b' is the resistance due to the quasi static laminar boundry layer as in the laminar flow transport efficiency is maximum; 'r_c' is the leaf surface resistance; gsto is stomatal conductance and gext is external leaf or cuticular resistance.

1.3.3 Calculation of POD_Y

To calculate POD_Y , the difference between hourly averaged value and threshold Y is taken for the daylight hours only. Y is fixed based on experimental data for the threshold that is associated with a crop yield loss of 5% in the respective cereal, fruit or vegetable.

1.3.4 Calculation of exceedance of flux based critical level

When the calculated POD_Y value exceeds the flux based critical level value than $CL_{exceedance}$ is calculated by taking the difference between POD_Y and critical level. It is calculated as:-

$$CLexceedance = PODY - critical\ level$$

1.4 Crop yield losses over the IGP and definition of the problem and targeted improvements through this study

Wheat is one of the most important crop over the IGP. The area under the wheat cultivation in Punjab is 3.4 million ha and with the production of 14.9 million tonnes. (ICAR). Due to the biomass burning and other anthropogenic activities the pollution is serious concerns for the crop yield loss over IGP. The precursor for the formation of Ozone is NOx and VOCs under the sunlight (V. Sinha, Kumar, & Sarkar, 2014). O_3 enters through the normal. It accumulates in the plants during the normal gas exchange.

Chapter 2

Materials and Methods

2.1 Site description

The experiment was performed with-in the IISER Mohali premises (30˚39’51.54 N 76˚43’55.65, SAS Nagar E). The IISER Mohali Campus is located in Sector 81, SAS Nagar, in North East part of the state Punjab in India. Climatically Punjab falls into the winter dry steppe climate zone in subtropical zone of northern hemisphere. There-fore this experiment was performed from November 2016 to April and November 2017 to April 2018.

The site is located in the Indo–Gangetic plane, a fertile region highly suitable for wheat cultivation. While the average wheat yield in India is comparatively low (2.7 t/ha) when compared with international averages (Lin & Huybers, 2012), wheat yield in Punjab generally vary between 4.5 and 5.1 (Envis Centre Punjab). The plot is located in an alluvial plain and the soil consists of layers loam to heavy loam near the top interlayered with sand to sandy loam soil below the surface. This type of soil is highly rich in nutrients and it is very suitable for crops like Wheat, Maize, Vegetables, and Paddy etc.

Meteorological data of the variables Temperature (T), relative humidity (RH), pressure (P), soil moisture (SM), leaf wetness (LW) and photosynthetic active radiation (PAR) was acquired from an agrometeorological station in the field. The derived variable water pressure deficit (VPD) was calculated from the data of agrometeorological station. In addition, ozone and carbon dioxide were measured at the IISER Mohali Central Atmospheric Chemistry Facility located on the rooftop of the Central Analytical Facility (CAF) IISER Mohali within 300 meters the field.

In addition to the data acquired during the field experiment itself, I compiled and analysed 7 years of meteorological 2011 to 2018 from the Met One meteorological sensor on the top of CAF consisting of tropospheric ozone concentration, solar radiation, precipitation, Wind Speed, Wind Direction, Ambient temperature, Relative humidity and derived variables such as vapour pressure deficit. From field agrometeorological station (Decagon EM50) 2 years (2016-17, 2017-18) of data was compiled consisting of ambient temperature, solar radiation, soil moisture, leaf wetness.

Figure 1 Location of Mohali in the Indian subcontinent, IISER campus and location of AQS and wheat field within the campus.

2.2 Agricultural methodologies

Preparation of Field:

Land preparation is an important step for the cultivation of any type of crop. It includes tillaging to diminish soil disturbance, harrowing to mix or overturn the soil, levelling for the uniform irrigation and rotavator is used to make the texture of soil fine which is good for the sowing.

Pre-sowing irrigation was applied to the experimental site and the weeds were pulled out manually with the hands. When the right moisture level is reached the field was ploughed using harrow. The organic manure was applied and the tractor rotavator were used to mix

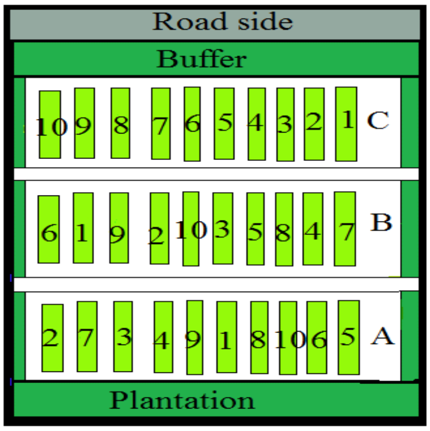
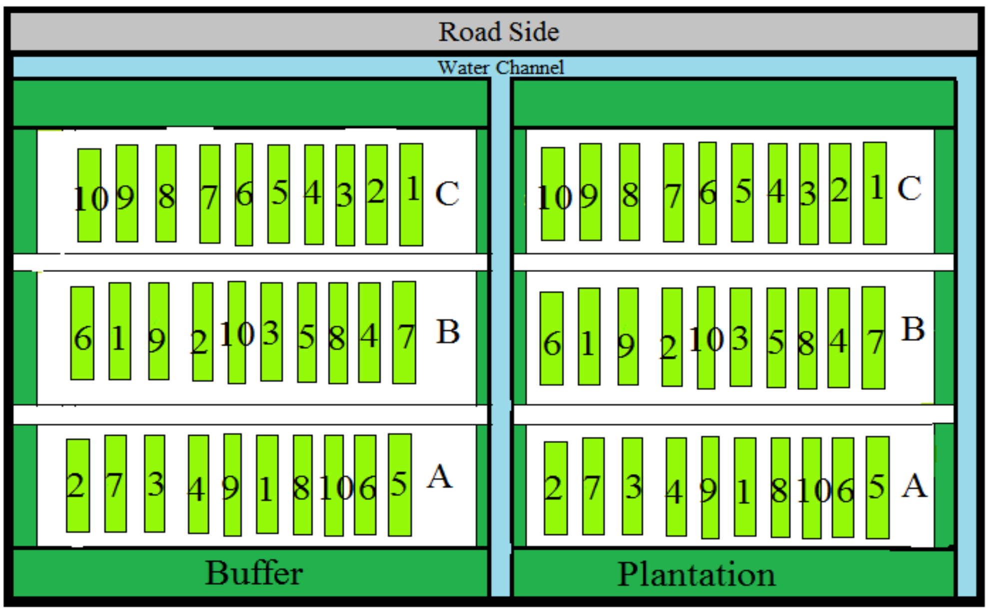


Figure 5: Layout of the field the season 2016-17

the manure to the soil and the field was cultivated. The experiment was sown manually using metallic rods for making a hole (2 inches) for planting seeds.

I have conducted this experiment twice, first in 2016-17 and then 2017-18. For both seasons the plan was different as given below:

For the growing season 2016-17 there was only one plot that contain 3 columns of 10 cultivars each and for the next growing season sowing was done in two plots each



1 = PBW550; 2 = HD2687; 3 = RAJ3765; 4 = HD2967; 5 = WH1105; 6 = GW322; 7 = C306; 8 = DBW88; 9&10 = From local farmeres(Unknown padigree)

Figure 9: Layout of the field the season 2017-18

containing 3 columns of 10 cultivars each. Both growing seasons local farmers pedigree was used for the plantation of buffer across the boundaries.

Planting basins were prepared according to the predefined plan for planting and irrigation as shown in Fig 2 for the season 2016-17 and in Fig 3 for the season 2017-2018

Seeds were sown with the following spacings:

- Total number of cultivars 10
- Replicates of each cultivars 3(in 2016-17) & 6 in (2017-18)
- Number of plants of each cultivar in a plot 30
- Rows of each cultivars in a plot 3
- Row to row inter cultivar distance in a plot 23 cm
- Cultivar to cultivar distance in a plot 44 cm
- Plant to plant distance 15 cm
- Sowing Depth 4 cm

Each hole was having two seeds. After the emergence the smaller and more unfit of the plants was removed.

To protect the wheat plants in the experimental plot from the rabbits frequenting the area, a'- chicken mesh was fixed on the boundaries.

With the help of water pump the irrigation was done. 1st irrigation was done 3-4 weeks after sowing. Total 5 times the field was irrigated. This was done after 20-25 days of every irrigation.

For the controlling of weeds no chemical was used. After every irrigation the weeds were pulled out manually with the help of trowel.

40 Kg/acre Urea was given to the wheat crop at the time of flag leaf stage.

2.3 Analytical Details

Leaf porometer: The leaf porometer is a tool to determine how open the stomata of a plant are to diffusion of trace gasses. It determines the stomatal conductance by measuring the diffusion of water vapour out of the inside of the leaf to the outside by putting the leaf in series with two RH sensors in a diffusion cell. The RH at the end point of the cell is kept at 10% with the help of an anhydrite dryer. The gradient in RH between the saturated air inside the leaf's stomata and the dry air at the end of the diffusion chamber triggers the movement of water vapour molecule from the inside of the leaf through the leaf porometer. A plastic bead is used as an agitator which helps in the mixing of the air and water vapour inside the cell.

The vapour flux is used to determine the stomatal conductance by using following equation:

$$F_{vapour} = g_{d2}\ (C1 - C2) \ \ldots\ldots (1)$$

Where F_{vapour} is the water vapour flux.

g_{d2} is the conductance

C1 & C2 are the mole fractions at node 1 & 2.

Working of leaf porometer:

Leaf porometer contains two known conductance elements (two humidity sensors) which measures the conductance in series of the leaf conductance and a temperature sensor in its aluminium head. This aluminium head prevents the temperature loss between the system and the surroundings. There is a desiccant chamber present at the bottom of the aluminium head which absorbs the water vapours as it reaches to the top of porometer from the leaf which forms a gradient of water vapor inside the diffusion path. This gradient is sensed by the two humidity sensors. The flux due to water vapor diffusion is calculated by the multiplication of the diffusion path across the sensors with the difference in the mole fraction of water vapor obtained from the sensors. The vapor flux will remain constant till the lid of the instrument is closed, because there is no migration of water vapours. Once the flux is known, stomatal conductance is calculated by the instrument itself.

Equation (1) is used to calculate the flux of the water vapours.

The parameters (g_{d2} & C) from equation (1) can be related to relative humidity by the equation

$$Ci = \frac{h_r\, e_s(Ta)}{P_{atm}} \ldots\ldots\ldots\textbf{(2)}$$

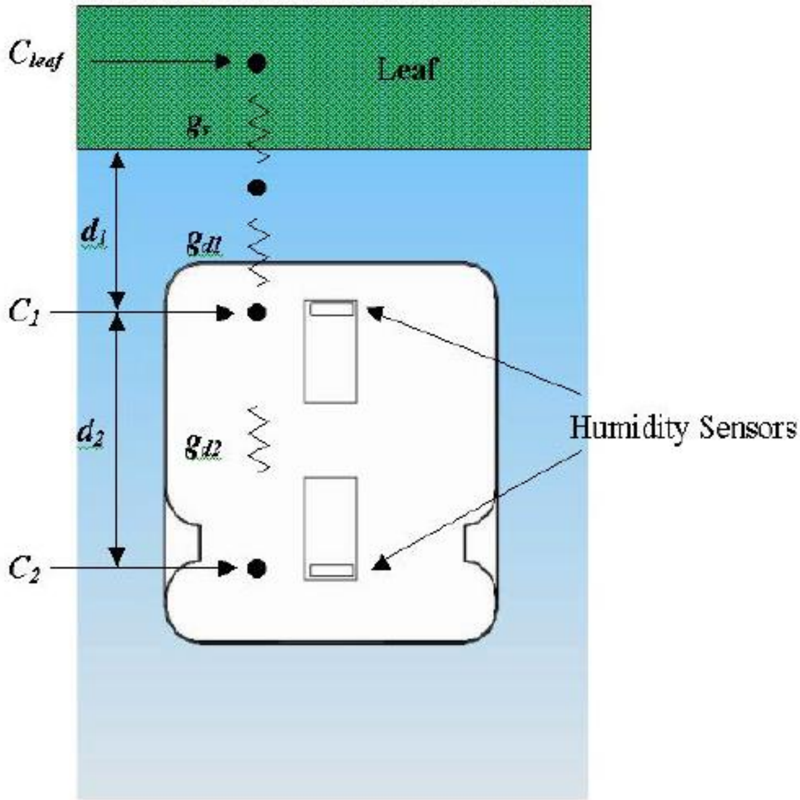


Figure 13: Function of leaf porometer (Reproduced with kind permission of the manufacturer from the instrument manual).

Where, h_r represents relative humidity

$e_s(Ta)$ is saturated vapour pressure at temperature Ta

P_{atm} represents atmospheric pressure

g_{d2} can be calculated from the equation

$$g_{d2} = \frac{\rho D_{vapour}}{d2} \ldots\ldots\ldots\textbf{(3)}$$

Where ρ and D_{vapour} represents the molar density of the air and diffusivity of the water vapour respectively.

Vapour flux is calculated using the following equation:

$$F_{vapour} = \left[\!\left[\frac{\rho D_{vapour}}{d2}\right]\!\right] \frac{1}{P_{atm}} [h_{r1}\, e_s(Ta1) - h_{r2}\, e_s(Ta2)] \ldots\ldots \mathbf{(4)}$$

The stomatal conductance (g_{stom}) is calculated using equation (1)

$$\boldsymbol{F_{vapour} = g_{d1+sto}\, (C_{leaf} - C_1) \ldots\ldots\ldots (5)}$$

The above equation includes the assumption that water vapour mole fraction at the leaf should be equal to 1. Using the formula of conductors in series we can estimate the stomatal conductance.

$$\frac{1}{g_{sto+d1}} = \frac{1}{g_{sto}} + \frac{1}{g_{d1}} \ldots\ldots \mathbf{(6)}$$

$$\frac{1}{g_{sto}} = \frac{1}{g_{sto+d1}} - \frac{1}{g_{d1}} \ldots\ldots\ldots \mathbf{(7)}$$

Air Quality station (CAF):

The 7 years meteorological data from 2011 to 2018 was taken for the wheat growing season that is from the month of November to April. AQS has different sensors like ozone sensor, pyranometer, RH sensor, Temperature sensor, Rain gauge, wind speed and wind direction sensors etc to record the different environmental parameters. The specifications of these sensors are given below:

- Ozone Sensor: A UV photometry sensor (Thermo Fisher Model 49i) was used to measure the ozone concentration with the time resolution of 1 minute. The uncertainty of the instrument is <6% and with the detection limit 1 nmol mol^{-1}.
- Pyranometer: (Model number- Met one 095) is the sensor that is designed for the measurement of solar radiation flux density (units Watts/m^2). The sensitivity of the sensor is 11 mV/kilo Watt m^2. The linearity of the sensor is ±1% from 0 to 1400 watts m^2 and the dependence on temperature of the instrument is ±1.5% constancy from -20° C to +40° C.

- RH sensor: A thin film polymer capacitor (Model number- 083e Met one) sensor was used to measure the measures the RH with the accuracy of ±2% from 0-100% humidity.
- Temperature Sensor: A thermistor (met one model 062A) sensor was used to record temperature within the range of -50^0 C to + 50^0 C. The accuracy of the instrument is ±0.1^0 C.
- Rain Gauge: It measures the amount of precipitation that falls. The tipping bucket of rain gauge allows for repeatable and good measurements.
- Wind Speed: Metone 010C sensor was used to document wind speed with the accuracy of ±1% and the resolution of <0.1 m/s.
- Wind Direction sensor: Metone 020C sensor was used to record wind direction with the accuracy of ±3° and resolution of < 0.1 °.

Agriculture meteorological Station (EM50G data logger):

The decagon met station was installed in the field. It was used to measure the various environmental parameters such as temperature, PAR, solar radiation, precipitation, soil moisture, Rh and leaf wetness.

- Temperature sensor: VP-4 temperature sensor was used to record the temperature within the range of -40° C to 80° C with the accuracy range ±0.5 from 5 to 40°C and for outside this range ±1°C.
- PAR & Radiation sensor: QSO-S PAR Photon Flux Sensor was used to record the PAR within the spectral range of 400-700nm with the accuracy of ±5% and PYR solar radiation sensor was used to measure solar radiation within the spectral range of 380-1120 nm with the accuracy of ±5%.
- LWS: PHYTOS31 LWS was used to measure the presence of moisture on the leaves.
- SM sensor: GS-1 high frequency soil moisture device was used to measure the dielectric constant of the soil. For long term monitoring it is buried in the soil.
- Rain Gauge Sensor: ECRN-100 high resolution rain gauge double spoon tipping bucket was used to record the precipitation of 0.2mm rainfall per tip.

2.4 Cultivars in this study

In the first growing season 2016-17 all 9 cultivars were studied and in the next season five of them were studied which are PBW550, HD2687, RAJ3765, GW322, C306, DBW388, HD2967, WH1105.One cultivar was taken from the local farmers. The details of these cultivars are given below:

PBW550: This is superior cultivar for late sown and irrigated cropland for entire north-west Indo-Gangetic Plain (IGP). It was developed in PAU in 2007 and is known for good grain quality and early maturity. It is resistant to pest and most fungal infections. It is less prone to thermal heat stress and has a maturity time of 146 days.

Photograph 1: PBW550 17 days after anthesis

HD2687: This variety is also known as "Shreshtha" and was developed by IARI New Delhi. This cultivar is suitable for timely sown and irrigated regions. The plants acquire the height of 90-100 cms by the maturity time. The plants take 132-136 days to maturity. The variety is good for chapati making.

Photograph 2: HD2687 7 days after anthesis

Photograph 3: RAJ 3765 around anthesis time

RAJ3765: This variety was developed by RARI Durgapura. It is suitable early sown, late sown and for irrigated conditions. The average yield is 36-40 quintal per hectare. By the maturity time the plants attain height of 80-90 cm. This variety is very good for making chapati, biscuit and bread.

Photograph 4: GW322 around anthesis time

GW322: This variety was developed by GAU Vijapur. This is timely sown variety and suitable for irrigated conditions. The average yield is 41-45 quintal per hectare. By the maturity time plants takes the height of 90-100 cm. It is resistant to stem rust and leaf rust. It takes 126-134 days to mature. It is good for chapati making.

C306: This variety was developed by HAU Hissar. It is suitable for timely sown and rainfed conditions. The variety gives the average yield of 26-30 quintal per hectare. For maturity variety takes 136-140 days. By the maturity time the plants attain the height of 110-120 cm. It is very good for making the chapati.

DBW88: It is suitable for timely sown and irrigated conditions. It is resistant to yellow and brown rust. Its grains have high protein content. Plants attain the height of 80-95 cm by the maturity.

Photograph 5: C306 shortly after anthesis time

Photograph 6: DBW88 during anthesis time

HD2967: This is a double dwarf variety developed in PAU (2011). It is suitable for irrigated or rain fed timely sown conditions. It has abundant tillering. It is resistant to yellow rust, brown rust and kernel bunt. It takes about 157 days to reach maturity. It is good for chapati making and has good protein content.

Photograph 7: HD2967 8 days after anthesis

WH1105: This variety was developed by HAU Hissar. It is suitable for irrigated and timely sown conditions. The plants take 145 days to maturity with the plant's height of 95-100 cms.

Local seed: This was the unknown pedigree and directly taken from the farmers. This was cultivated for the comparison. The plants attain the height of 95-100 cms by the maturity time.

Photograph 8: WH1105 16 days after anthesis

Photograph 9: Local farmers cultivar during anthesis

2.5 Data processing of Meteorological data

The raw data taken from the AQS CAF and agriculture meteorological station from the field. All the raw data further processed in Microsoft excel 2016.

The data processing includes the followings steps.

- The data is daily hourly averaged.
- Data gaps are filled by is filled using interpolation(averaging) of the data occurring for the same time from previous and later year's data.
- The further data processing depends on the nature of the parameter to be looked at. For example, for temperature the thermal sum, the accumulated daily average temperature over a threshold of 0°C is very important. To calculate the thermal sum, the temperature is averaged for each day of the growing seasons and each year separately. Subsequently the data is summed over all the days prior to the day under consideration starting from the first day after sowing. This is done for each year separately. However, for some calculations, e.g. the phenology function of the DO_3SE model the thermal sum must be expressed as thermal sum with respect to Anthesis, with thermals sums less than the value at which Anthesis was reached having negative numbers and values between anthesis and maturity having positive numbers. To calculate the thermal sum with respect to Anthesis the average cultivar specific thermal sum to Anthesis determined in the two growing seasons is subtracted from the thermal sum of each day. So while the thermal sum for e.g. 130 days after sowing (DAS) is identical for all cultivars for the growing season 2017-2018, the thermal sum with respect to Anthesis for that same day differs from cultivar to cultivar by up to 250°C.
- To identify the typical meteorological conditions for each day of the growing season parameters such as the 24-hour average, minimum and maximum temperature are calculated separately for each year. Subsequently the average, median, minimum and maximum average temperature, minimum temperature and maximum temperature for that particular day of the growing season is determined from seven years of meteorological data. This helps to calculate when the wheat will reach a particular growth year in an average year, unusually cold or extremely hot year, when the vernalisation requirements of a particular cultivar will be met and how many days the wheat is exposed to extreme temperature stress.

- The data is averaged over the average of each environmental parameter for same hour for the time period of 7 years
- With the help of averaged data, the maximum, minimum and median is calculated for same hour for the 7 years.

2.6 Accuracy, Precision and calibration of the leaf porometer

For taking the precise readings of the stomatal conductance the two sensors head must agree well with each other. To avoid inaccurate conductance measurement and the good data quality the instrument was calibrated frequently within the temperature change of >15^0 C.

The following steps was involved for the automatic calibration:

- The instrument must be in thermal equilibrium before starting the calibration, it takes 10-15 minute to reach the equilibrium if we take the porometer from the air condition environment to the field conditions.
- The next step is to check the desiccant if it is blue means no need to change it if it is purple means the desiccant is exhausted so change the exhausted desiccant.
- Both the sensors must be in balance within the range of 2% of RH of each other. This can be done by shaking the agitation bead so that the air in diffusion path mixed well.
- Use tweezers to wet the filter paper. Don't touch the filter paper to avoid the contamination. To give the 100% Rh the paper should be wet enough.
- Further the calibration process performed on the plastic calibration plate with known conductance of 240 mmol m^{-2} s^{-1} which has a drilled hole in the middle. This hole is covered by the moist filter paper. If the filter paper is too dry, wet it again if this happens during the calibration then repeat the calibration process. If the filter paper gets too wet the free water get pulled into the hole of the calibration plate, the hole dimensions will be influenced by the surface tension consequently changing the conductance.

- The calibration will be saved automatically if three consecutive measurements are all within 7.5% of each other.

For the manual calibration the measurements of the filter paper were taken frequently

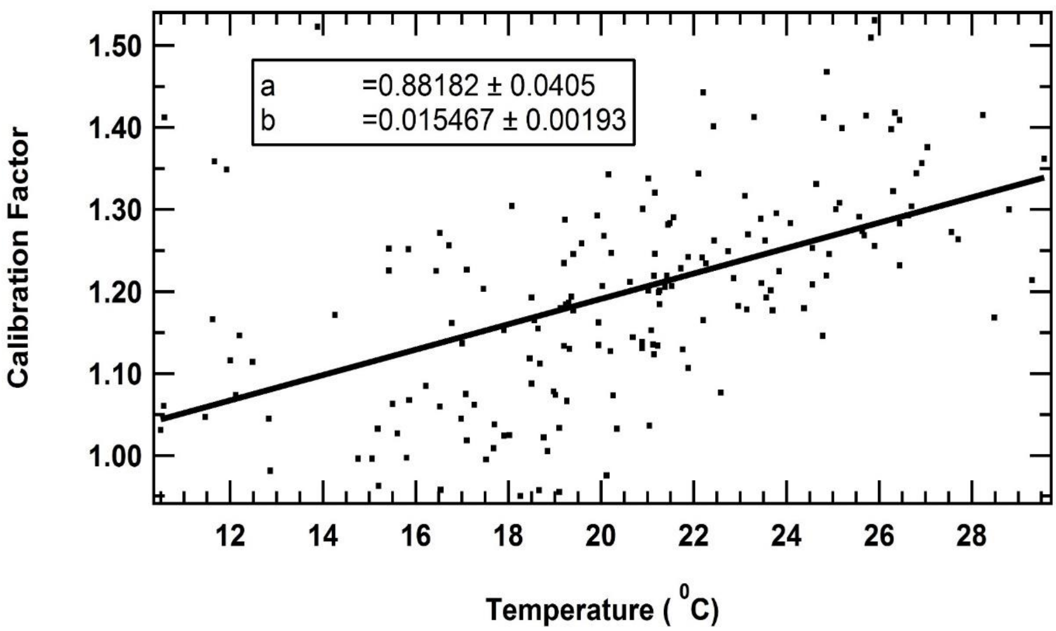


Figure 17: Calibration factor as a function of temperature

within the interval of 2 hours or 5^0 C change in the temperature. For every calibration 5 filter paper readings were taken. The calibration factor was calculated

$$\text{Calibration factor} = \frac{\text{measured calibration}}{\text{true calibration}} \qquad (1)$$

And the corresponding temperature was also taken to that measurements. The calibration factor is plotted against the average temperature.

This linear equation was then used to calculate the corrected calibration factor for the measurements done at different temperatures, buy replacing the x by T in the above linear equation. Then the corrected calibration factor was used to correct the measured values of the stomatal conductance.

$$Calibration\ factor = \frac{measured\ calibration}{true\ calibration} = \frac{measured\ unknown}{true\ unknown} \qquad (2)$$

$$true\ unknown = \frac{measured\ unknown}{calibration\ factor} \qquad (3)$$

Chapter 3

Results and Discussion

3.1 Typical meteorological conditions during the wheat growing season

Wheat growth and yield strongly depends on favourable meteorological conditions during each growth stage of the crop. In fact, crop models such as the Decision Support System for Agrotechnology Transfer (DSSAT) model (Hoogenboom et al. 2017, Jones et al. 2003) or the the WOrld FOod STudies WOFOST model (Van Diepen et al., 1989, Ceglara et al. 2018) use thermal time as the basis for crop development rate. The temperature is accumulated above a base temperature of 0°C and corrected for vernalisation (exposure to cold to induce reproductive growth) and photoperiod. Above a temperature of 30°C the developmental rate is considered to remain constant (Ceglara et al. 2018) and above a maximum temperature of 34°C thermal stress is considered to hasten leaf senescence (Asseng et al. 2011). As long as nutrients and soil moisture are not limiting factors temperature, is the most important parameter for predicting wheat development and growth. Hence, I first discuss the impact of the typical temperature during the wheat growing season and wheat growth and estimated yields for three hypothetical sowing dates: 1st of November, 15th of November and 1st of December.

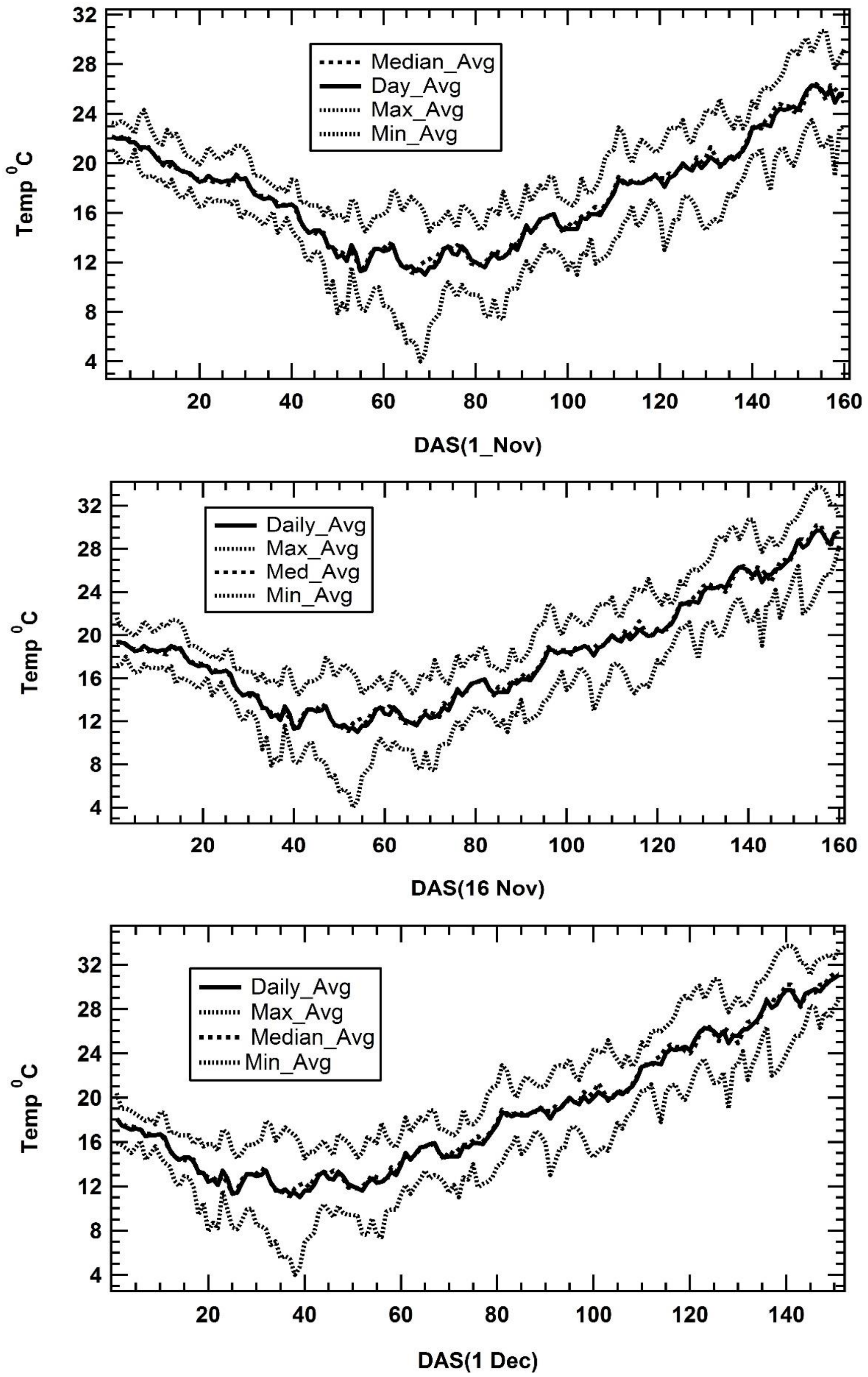


Figure 21: 7-year average, median, minimum and maximum of the 24-hour average temperature and with three sowing dates, i.e 1st November, 16th November and 1 December.

temperature for the wheat sowing season for all three sowing dates. The data is plotted as a function of the number of days after sowing (DAS). Asseng et al. 2011, describe that the maximum leaf area growth happens, if the 24-hour average temperature remains within the window of 11°C -24°C.

It can be seen from Figure 6, that in an average year for an assumed sowing date of November 1st temperatures remain within that optimum window for the entire growth period from sowing till ~145 DAS (~60 days after Anthesis) when the crop is already approaching maturity. Temperatures sufficiently low to meet the vernalization requirements occur relatively late (55-75 DAS), and may delay reproductive growth of the wheat. Bhupinder Singh in his MSc Thesis submitted to Punjab Agricultural University Ludiana, however, reported no difference in the number of days to Anthesis (111 DAS) for WH1105 and PBW677 sown on 5th and 20th November and a shortening of the number of days for the same cultivars sown on 15th December (100 DAS) for the year 2015-16. In contrast Tilak Raj in his MS thesis submitted to the same University stated that for the cultivars PBW-343, PBW-502, PBW-550 and WH-542 reported that earlier sowing resulted in a larger average number of days to Anthesis for experiment conducted in 2008-2009 and 2009-2010. The cultivars took on average 115 days to Anthesis when sown on 15th October, 107 days to Anthesis when sown on 15th November and 95 days to Anthesis when sown on 15th December. This data seems to suggest that for some cultivars a delay in meeting the vernalisation requirement delays to onset of the reproductive growth.

For a 15th November sowing date, temperatures remain within the optimum window for leaf growth from the start of the growing season till approximately ~130 DAS (~40 days after Anthesis). However, due to the high temperatures post Anthesis, the observed grain filling period is shortened by approximately 10 days, when compared to a 1st November sowing. Temperatures cool enough to meet the vernalization requirements occur only during tillering (35-60 DAS), for this sowing date.

For a 1st of December sowing date, temperatures remain within the optimum window for leaf growth from the start of the growing season till approximately ~115 DAS (~20-25 days after Anthesis). Temperatures cool enough to meet the vernalization requirements occur only early during the growing season (20-45 DAS), for this sowing date. This could potentially affect the number of tillers formed on each plant. Once the heat waves start in a particular year, the 24-hour average temperature crosses 30°C shortly (within 5 days) of crossing 24 °C and daily maximum temperatures cross the temperature where leaf senescence is hastened. Consequently, the grain filling period of a 1st of December sowing is shortened by approximately 20 days, when compared to a 1st November sowing.

Figure 7 shows the7 year average, median, minimum and maximum of the daily maximum temperature for the same three sowing dates. While for a 1st of November sowing date temperatures capable of accelerating leaf senescence are not reached till the last week prior to the harvest date even in the hottest year, the average daily maximum temperature crosses

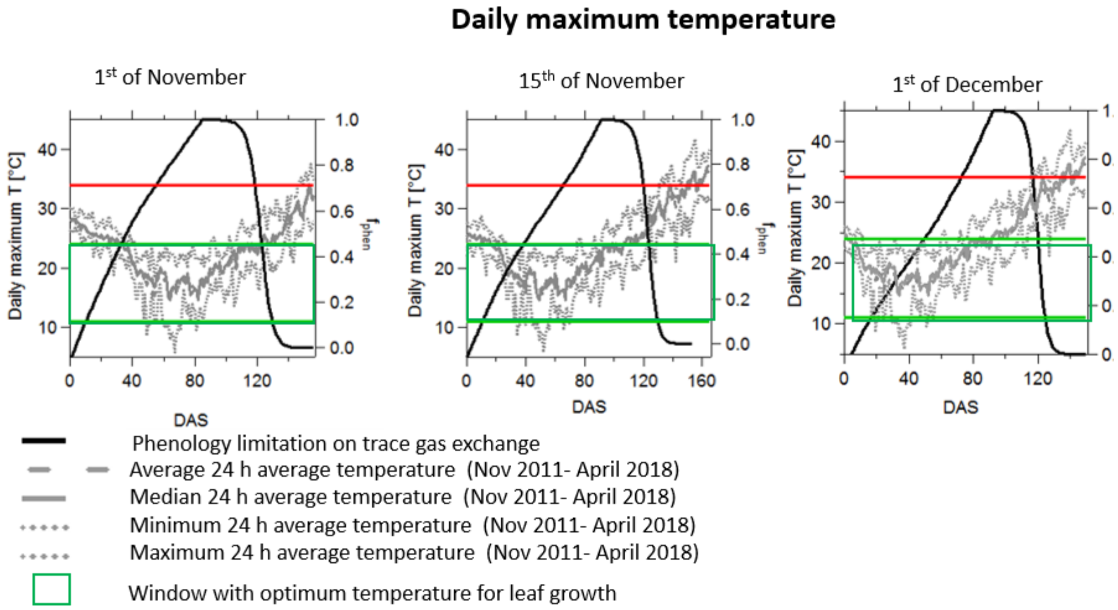


Figure 25: The7 year average, median, minimum and maximum of the daily maximum temperature

the 34 °C threshold ~140 DAS (~50 days after Anthesis). In a hot year, however, wheat sown on 15th November faces 8 days of accelerated leaf senescence due to thermal stress within the first 50 days after Anthesis. This results in a shortening of the grain filling period and yield losses. A delayed sowing on 1st December results in thermal stress staring from ~130 DAS (~25days after Anthesis) in an average year and 120 DAS (~15 days after Anthesis) in a hot year and significantly impacts yields.

Figure 8 shows the optimum photolysis window for three sowing dates. Optimal temperatures for photosynthesis are rare and occur for a very limited number of days (<20 days) in the entire growing season. For a 1st of November sowing date this happens at 30-42 DAS during tillering (which may impact the number of active tillers favourably) and 100-110 DAS i.e. around Anthesis time (which may impact the number of viable flowers

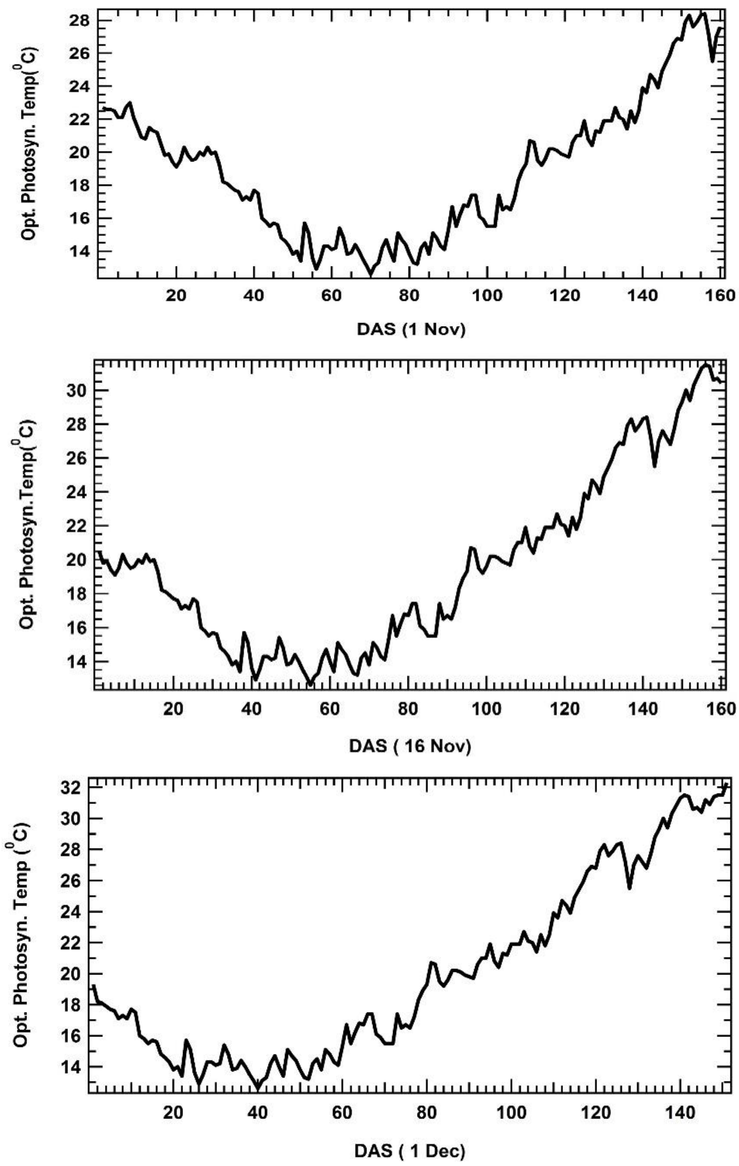


Figure 29: Optimum photolysis window for three hypothetical dates i.e 1^{st} November 15^{th} November and 1 December

and the early grain filling favourably). For a 15^{th} November sowing date, optimum temperatures for photosynthesis occur from 15-27 DAS and from 85-95 DAS. While for some cultivars Anthesis may still fall into this optimum temperature window, there are no days with optimum temperatures for photosynthesis after Anthesis for most cultivars, which may impact grain filling, although lethal temperatures which accelerate the loss of green leaf area are not reached till 40 days after Anthesis. For a 1^{st} of December sowing date, optimum temperatures for photosynthesis occur prior to or just after emergence (0-12

DAS), when they are of little consequence and from 70-80 DAS, a time window that corresponds to the flag leaf stage.

o estimate the ambient level and exposure of the wheat to ozone, ozone is monitored. Exporsure can be approximated using the M7 metrics, which corresponds to the 7 hour average ozone between 9:00 am and 16: am each day, while for estimating plant uptake parameters such as VDP, temperature, soil moisture and light must be looked at. The various meteorological parameters were calculated by calculating the average for each 24 hours and then determining the average average using 6 years data. Where appropriate and more meaningful (e.g. solar radiation as a proxy for fog or thick cloud cover), the 24-hour

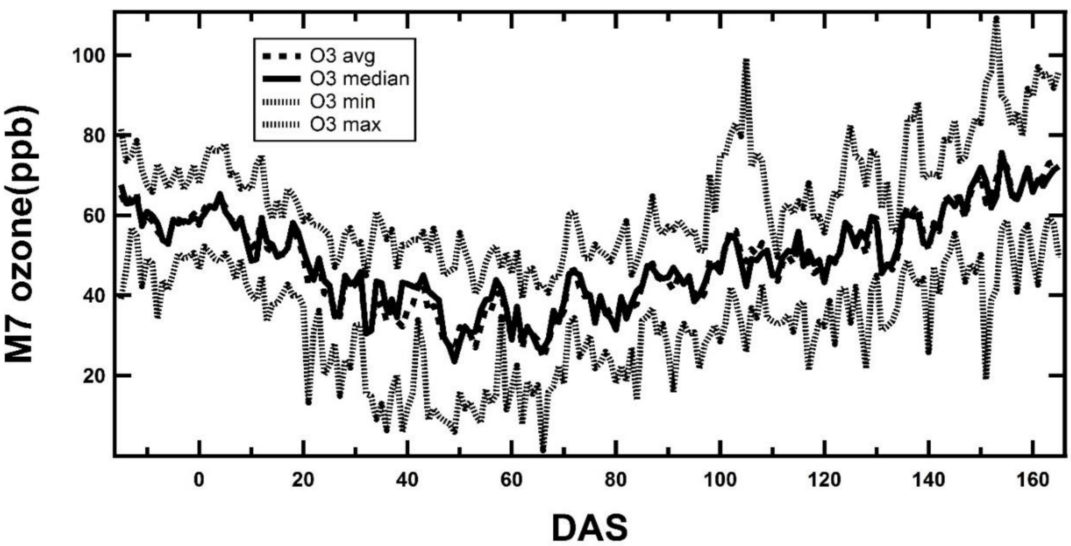


Figure 37: Typical meteorological conditions based on 5 growing seasons from 2011-2018

maximum was determined for each day individually and the 6-year average maximum was calculated subsequently.

Figure 9 shows that the concentration of ozone followed the similar trend as of the VPD, Temperature, Solar radiation and Wind speed. °

In Figure 9 I have studied the ozone mixing ratio for 7 years during the wheat growing season (November to April) from 9:00 hours to 15:00 hours for a 15th of November sowing date. It can be seen that the "safe" M7 of 25 ppb is rare and occur only in exceptionally foggy years. In general, the M7 index is averaged for all days from flag leaf stage (~70

DAS) to maturity (~140 DAS) to estimate crop yield losses. For a 15th November sowing date the estimated relative yield loss RYL in an average year amounts to 27%. From the above graph the ozone concentration is lowest in between 30-70 days after sowing which comes during December-January. Anthesis occurs between 95-110 DAS wheat can be influenced by ozone during this critical stage as high exposure can promote pollen sterility. The M7 during this time period has a large year to year variability and varies from 30-40 ppb in a cool year with many western disturbances to >80 ppb in a bad year with early heat waves. This means, wheat sown on November 15th can suffer highly variable ozone related crop yield losses.

Figure 10 shows that during an average year, the daily solar radiation maximum is so high, that photosynthesis is not limited by the available radiation during the peak daylight lowers. Due to increased solar radiation during advanced growth stage the temperature also increases which exaggerates the evaporation rate results in drying of soil and leaf moisture. The increment in temperature leads to higher the phenology function during this time window and homeostasis is attained by monitoring the temperature of the leaf. The increase in temperature during the advanced growth stage facilitate the invasion of ozone into stomata in particular in the presence of sufficient soil moistures, as the wheat cultivars may use evapotranspiration to cool the leaf as long as sufficient moisture transport from the roots can be maintained.

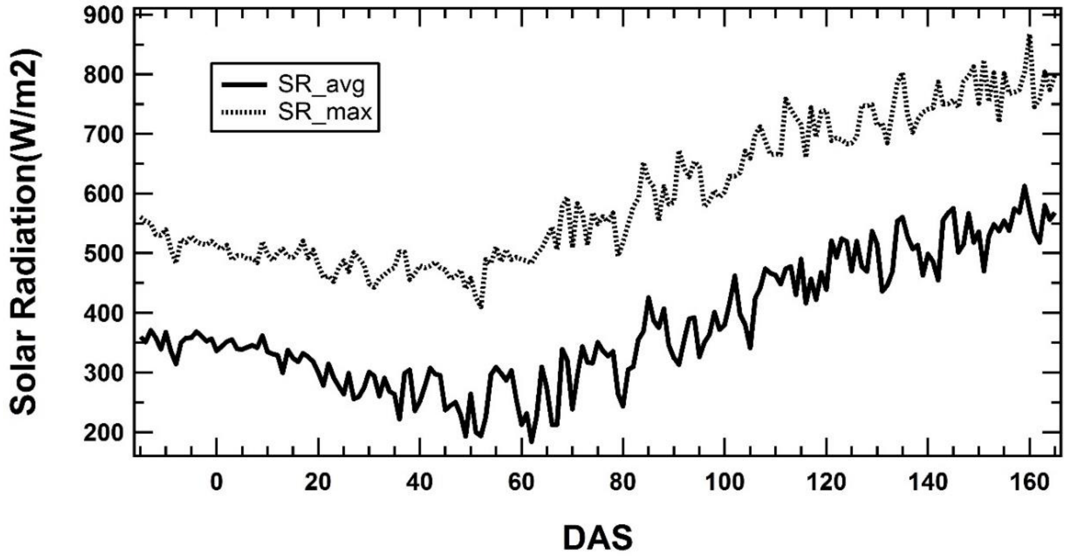


Figure 45: Typical meteorological conditions based on 5 growing seasons from 2011-2018

Figure 11 shows the average and maximum wind speed. It can be easily deciphering from the above plot that during cold months wind speed is lowest and after this time window there is an increase in wind speed due to the low-pressure regions formed by increase in temperature. There is a decrease in the boundary layer resistance due to higher wind speed which results in increasing stomatal conductance. So, this parameter also leads in significant addition of ozone into stomata.

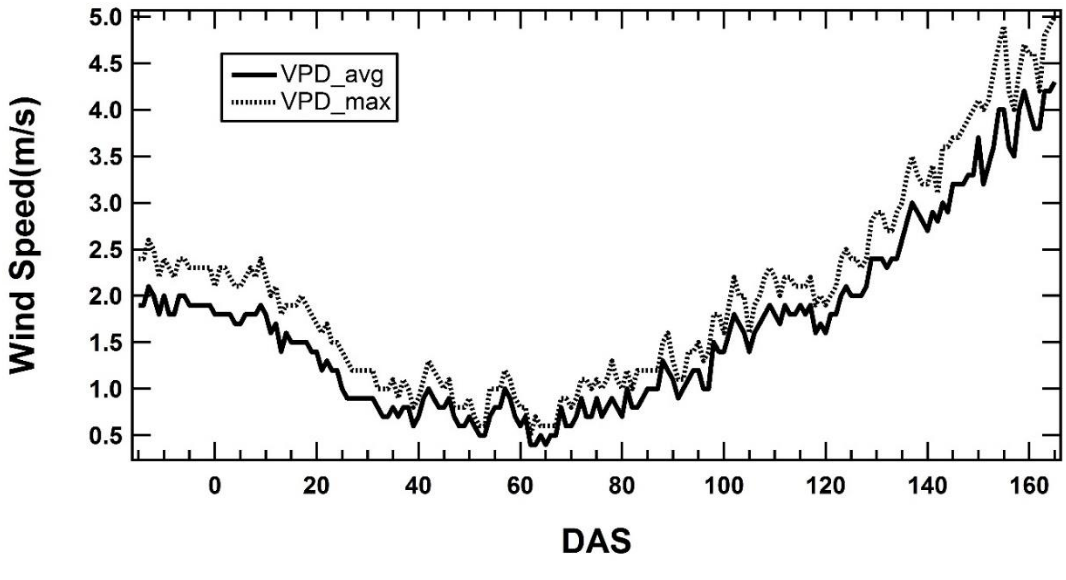


Figure 41: Typical meteorological conditions based on 5 growing seasons from 2011-2018

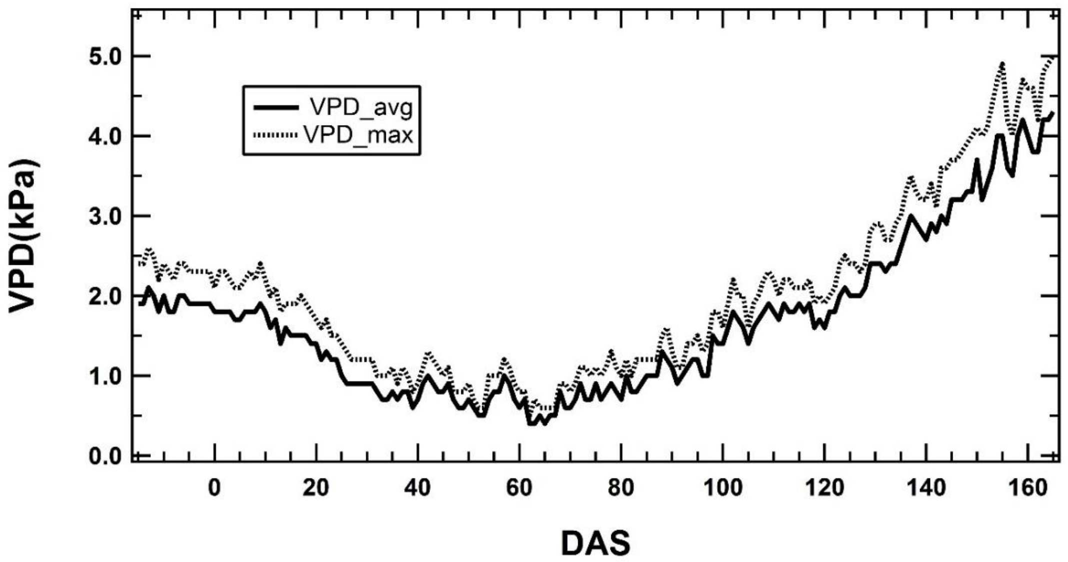


Figure 49: Typical meteorological conditions based on 5 growing seasons from 2011-2018

During the end of the growing stage drying condition due to hot dry winds with high wind speeds increases. If VPD_max of the cultivars is higher during this time it will keep its stomata open which exaggerate the accumulation of ozone during these dry conditions because of the enhanced dry deposition flux. There exist some cultivars having lower VPD_max keeps their stomata closed during these drier conditions.

3.2 Specific meteorological conditions during the 2017-2018 wheat growing season

Figure 13 shows the temperature, PAR, VPD and soil moisture during the during season 2017-18. The maximum temperature of 2.4 ^{0} C was observed on 9th January at 07:00 hours after 56 DAS and the maximum temperature around 37 ^{0}C was observed in the end of growing season during day light hours around 14:30 hours when the crop is already mature. In the growing season 2017-18 there is an continues increase in the temperature from march to end of the growing season. Till march the temperature fluctuates between 10-25 ^{0}C.

There is an increase in VPD towards end of growing season which indicates drying conditions. At the time of anthesis the soil moisture was dropped that can be expected that impact on lower stomatal conductance and grain filling stage negatively.

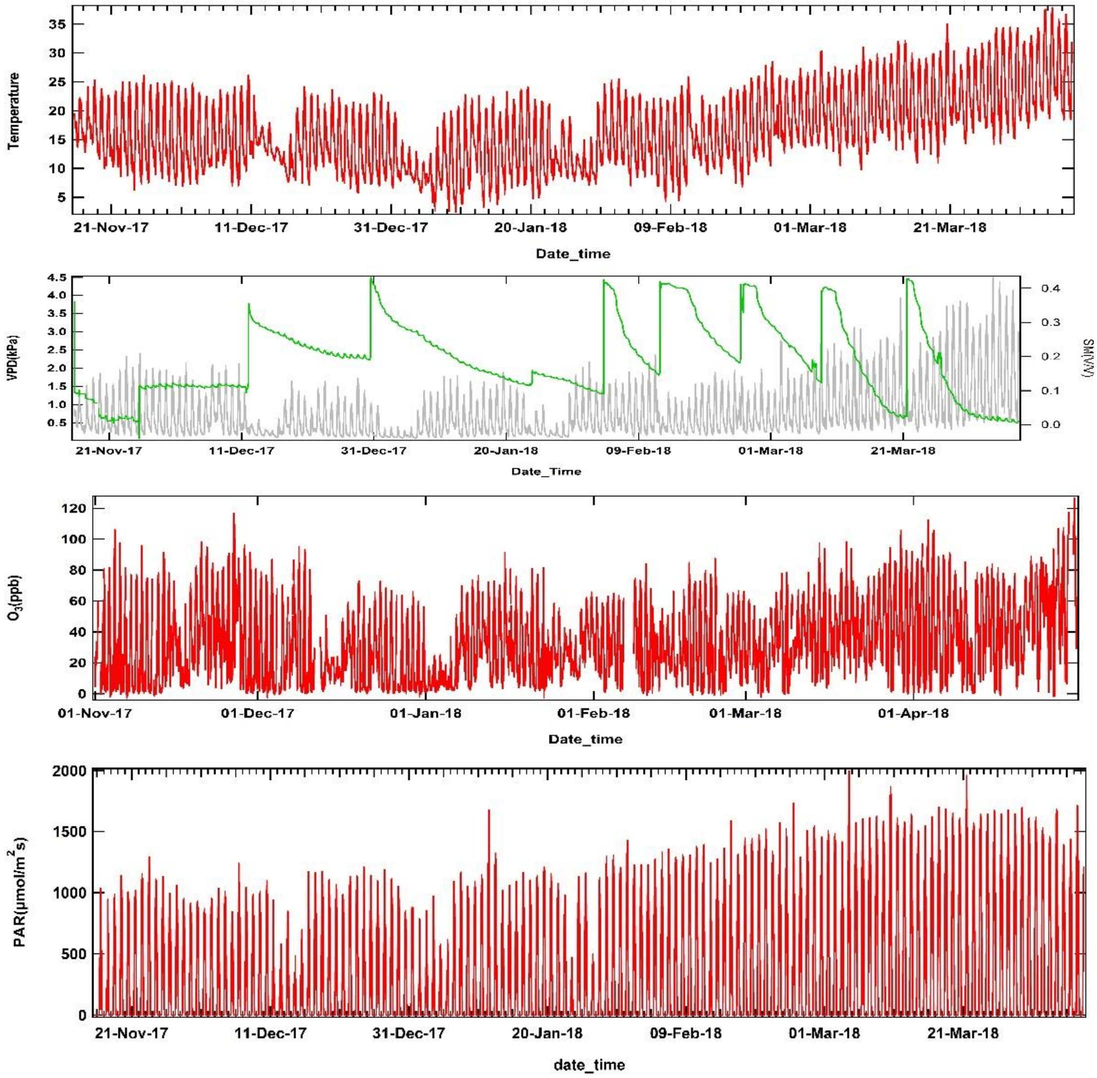


Figure 53: Temperature, SM, VPD, O_3, and PAR for the growing season 2017-18.

Ozone mixing ratios were higher from starting to growing season till December and then again increase in the end of growing season when the PAR and temperature is already higher.

Figure 14 shows the diel and whisker plot for PAR, Temperature, VPD and Ozone. It is clearly visible from the picture that everyday sun rises around 07:00 AM and the temperature starts rising after 1 hour. Solar radiation is high around 12:00 PM. Ozone is at its peak around 14:00 to 16:00 hours and at the same time VPD is also higher around this time.

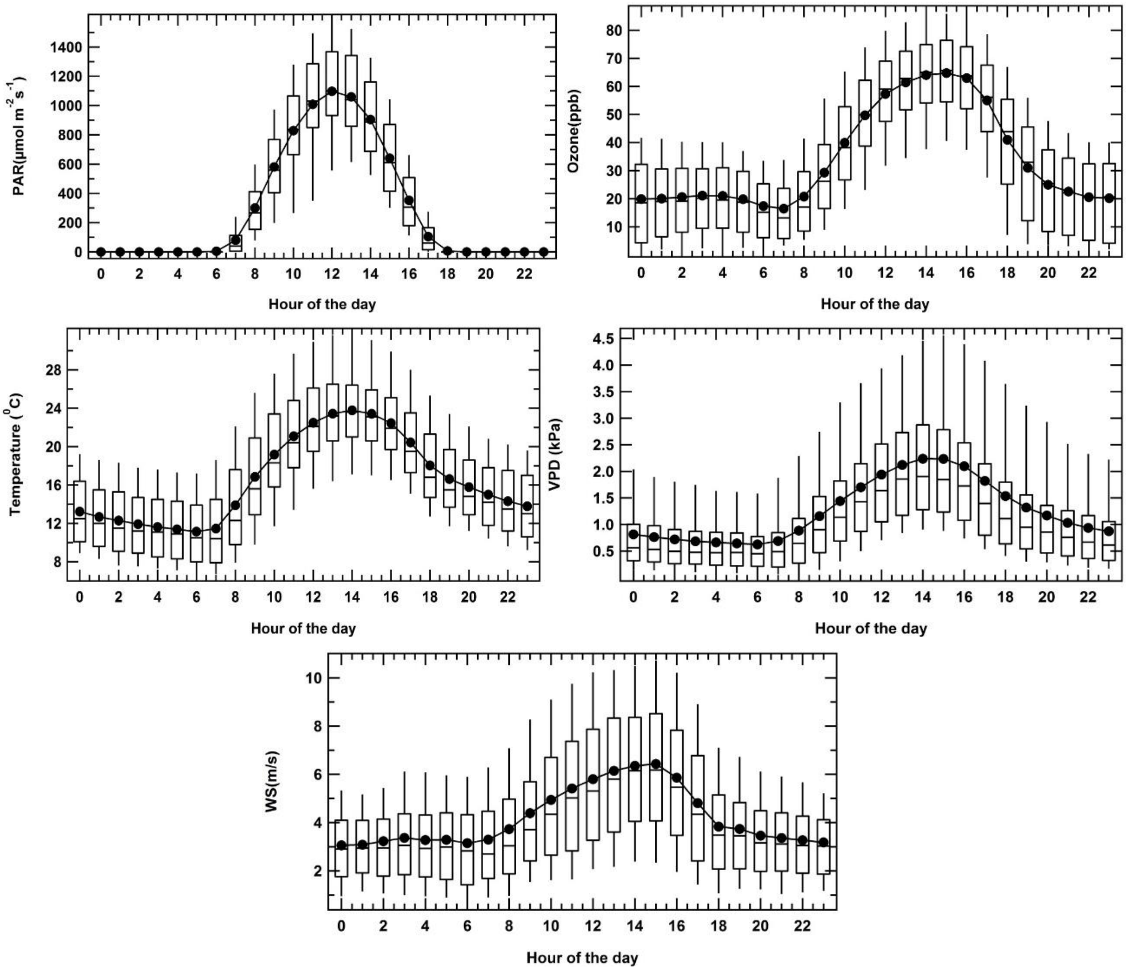


Figure 57 Diel box and whisker plot for PAR, Ozone, Temperature, VPD and Wind Speed for the growing season 2017-18. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90th and 10th percentile of the data.

3.3 Diel rhythms in plant stomatal conductance:

Figure 15 shows the variation in stomatal conductance of cultivar C306 against the time of the day. The conductance was measured at the different time of the day.

It is clearly seen from the graph that the stomatal conductance increases prior to/around sunrise, although the graph is noisy for those hours because as long as dew is on the leaves stomatal conductance cannot be measured. From 10 am onwards, there is a much large number of measurements and days with observations for each hour. Conductance remains high throughout day time because the stomata remains open during the day time and close during sunset. The stomatal conductance decreases when the light is low for the photosynthesis.

In the case of C306 at 12:00 and 15:00 hours the maximum stomatal conductance was observed. The maximum gsto was 550 mmol/m^{2}s The dip at 14:00 is a statistical artefact caused due to the fact that prior to 45 DAS all readings were taken in this hour only and conductance is low on your leafes. After 45 DAS readings were taken during all hours of the day after the dew evaporated without bias. In between these hours the stomatal conductance, VPD, Temperature, Ozone and PAR values decreased. The optimum

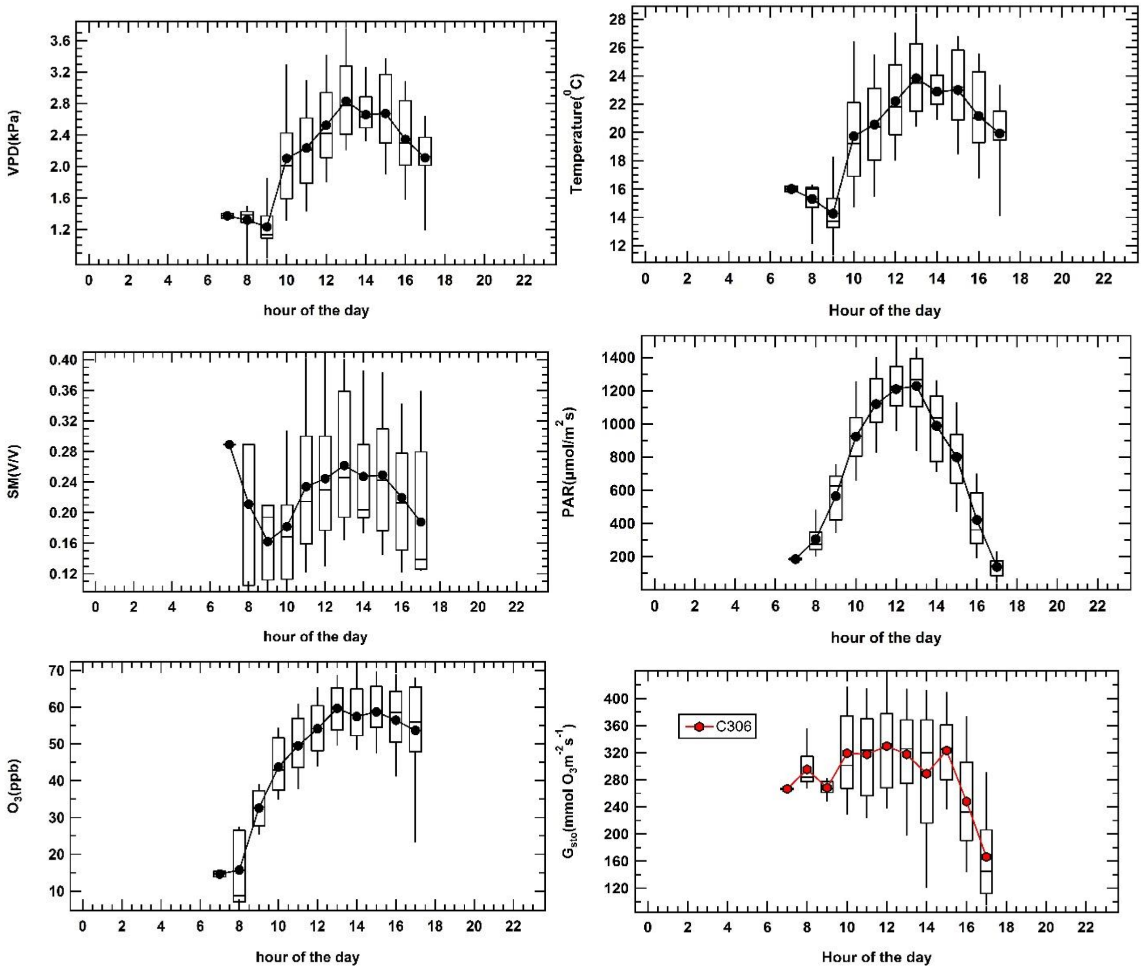


Figure 61: Diel box and whisker plot for the stomatal conductance of the C306 along with different environmental parameters for the 2017-18 growing season. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90th and 10th percentile of the data.

temperature for this cultivar is 25^0C. This cultivar is resistant for drought conditions because it can open its stomata under very low moisture conditions.

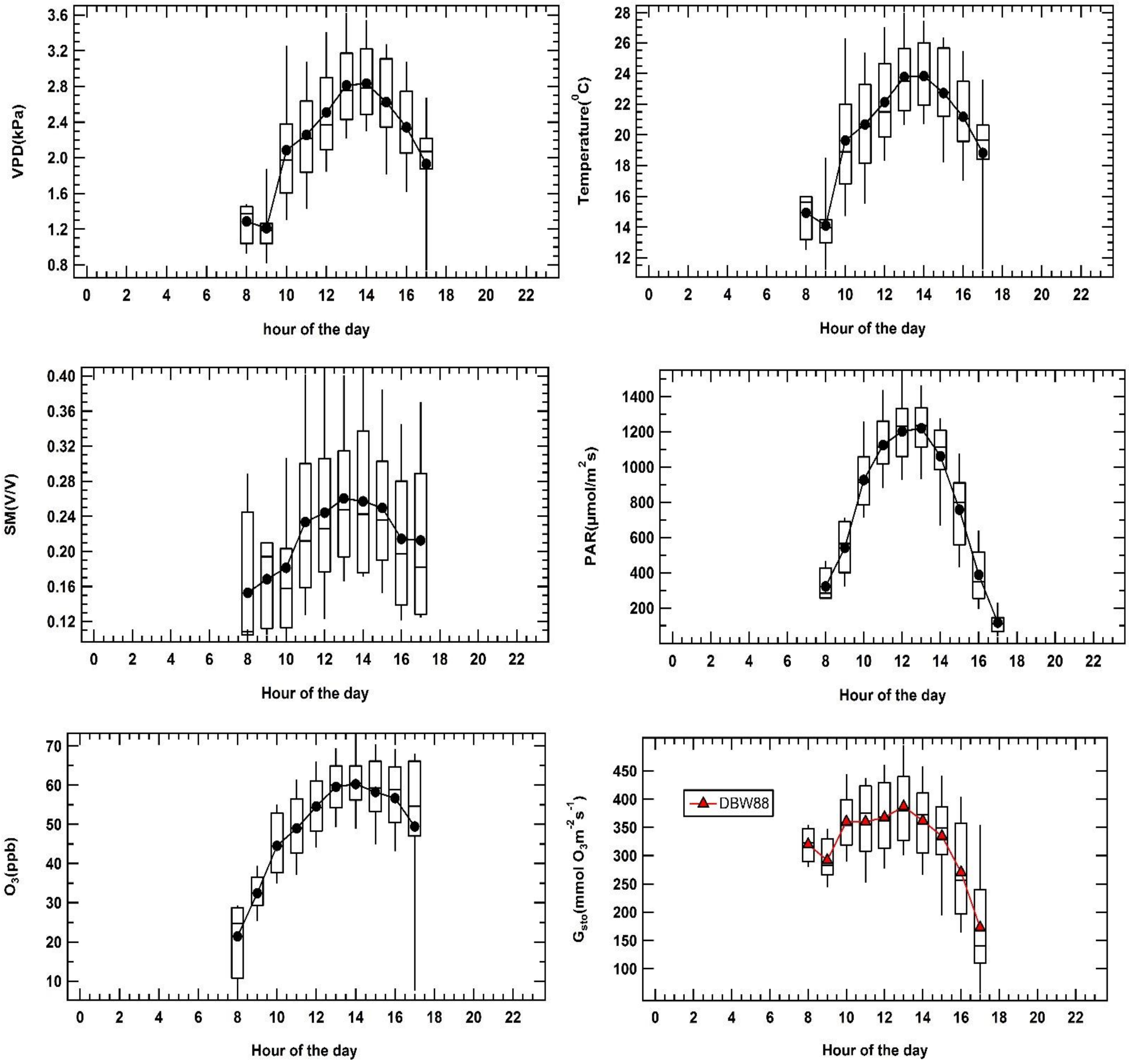


Figure 65: Diel box and whisker plot for the stomatal conductance of the cultivar DBW88 along with different environmental parameters for the 2017-18 growing season. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25^{th} percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90^{th} and 10^{th} percentile of the data.

In case of DBW88, the maximum stomatal conductance was observed at around 13:00 Hrs. The maximum gsto was 570 mmol O_3 m-^{2} s-^{1}This cultivar is preferable for cultivation in low light conditions because it has low alpha value. It can be seen that high VDP does not result in stomatal closure. Instead temperatures below the optimum temperature are most frequently responsible for stomata closure.

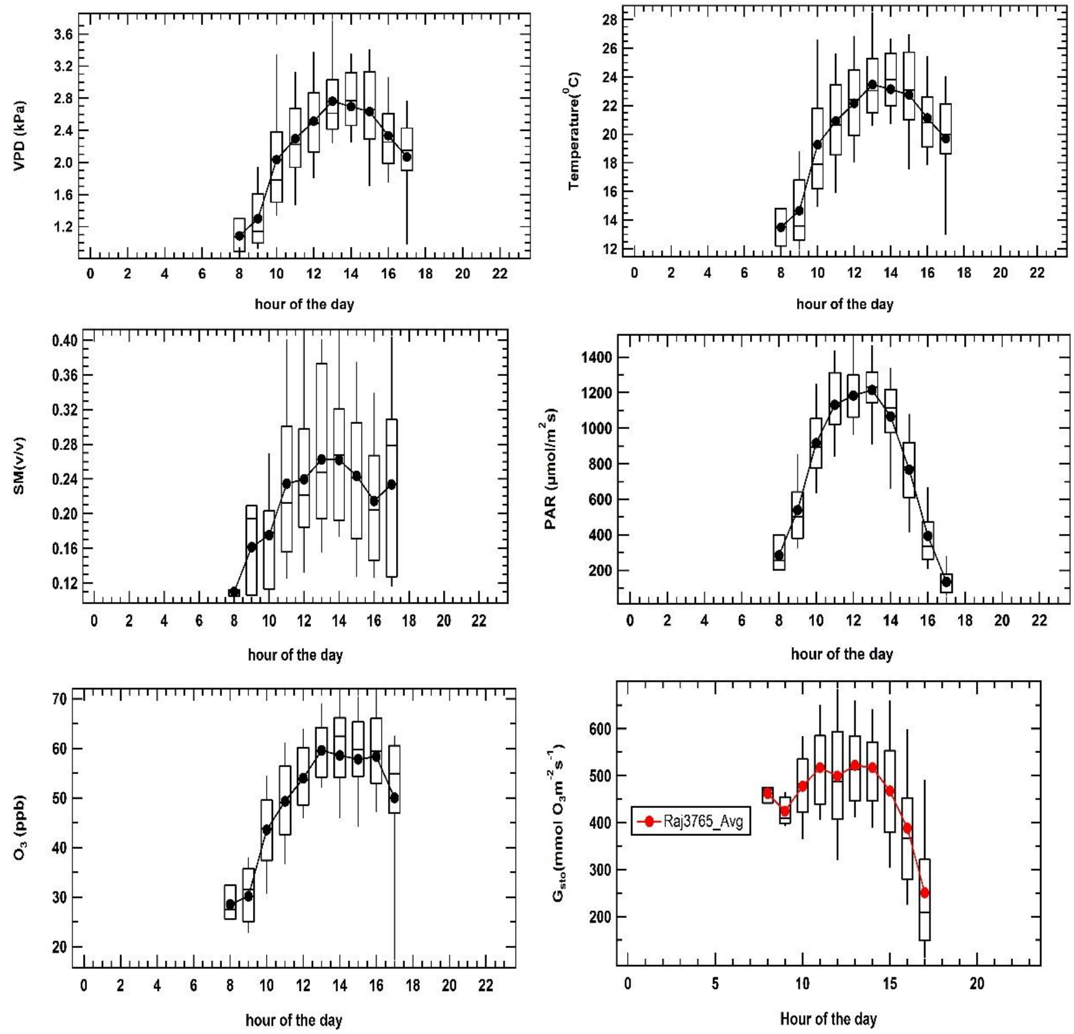


Figure 69: Diel box and whisker plot for the stomatal conductance of the RAJ3765 along with different environmental parameters for the 2017-18 growing season. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90th and 10th percentile of the data.

For cultivar RAJ3765 the PAR, Temperature, Ozone, VPD values are higher during 11:00 to 14:00 hours. It can be seen that high VDP does not result in stomatal closure. Instead temperatures below the optimum are most frequently responsible for closure but occur at times when ozone concentrations are low. The stomata is open during this time window and gsto max of this cultivar is high (720 mmol O_3 $m^{-2}s^{-1}$) because of which more ozone will get accumulate inside stomata which leads to higher yield loss as compared to other cultivars.

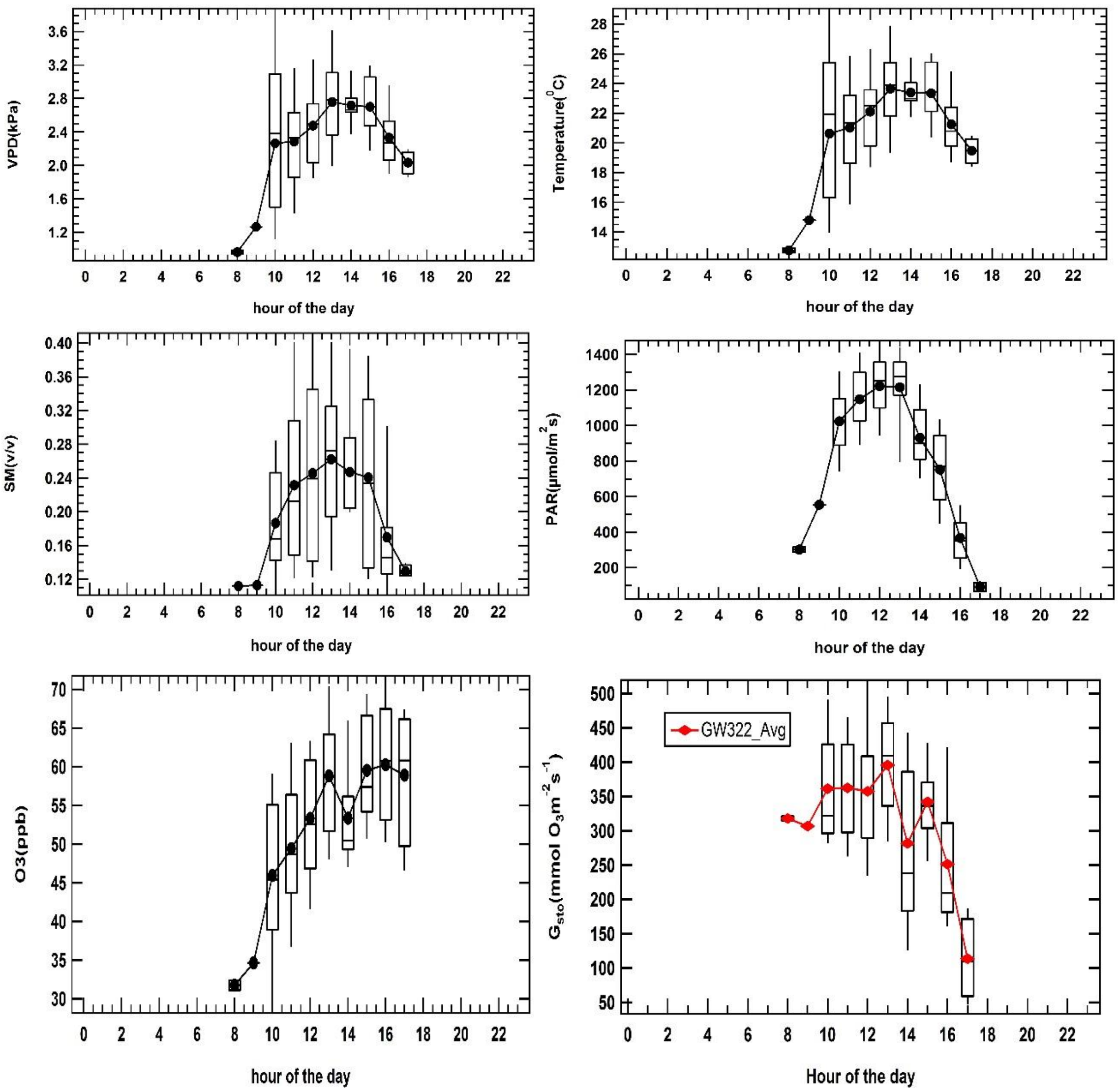


Figure 73: Diel box and whisker plot for the stomatal conductance of GW322 along with different environmental parameters for the 2017-18 growing season. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90th and 10th percentile of the data.

The cultivar GW322 showed higher stomatal conductance at around 13:00 hours. The maximum stomatal conductance was 570 mmol O_3 m-^{2} s-^{1}. Just like in the case of C306 the decrease in stomatal conductance at 14:00 hours is a statistical artefact due to a large number of readings taken during the hour at a very early growth stage. At the same time other environmental parameters (PAR, VPD, Temperature, SM) indicate that showed higher values of VDP or low SM do not induce stomatal closure leading to less yield loss due to enhanced photosynthesis.

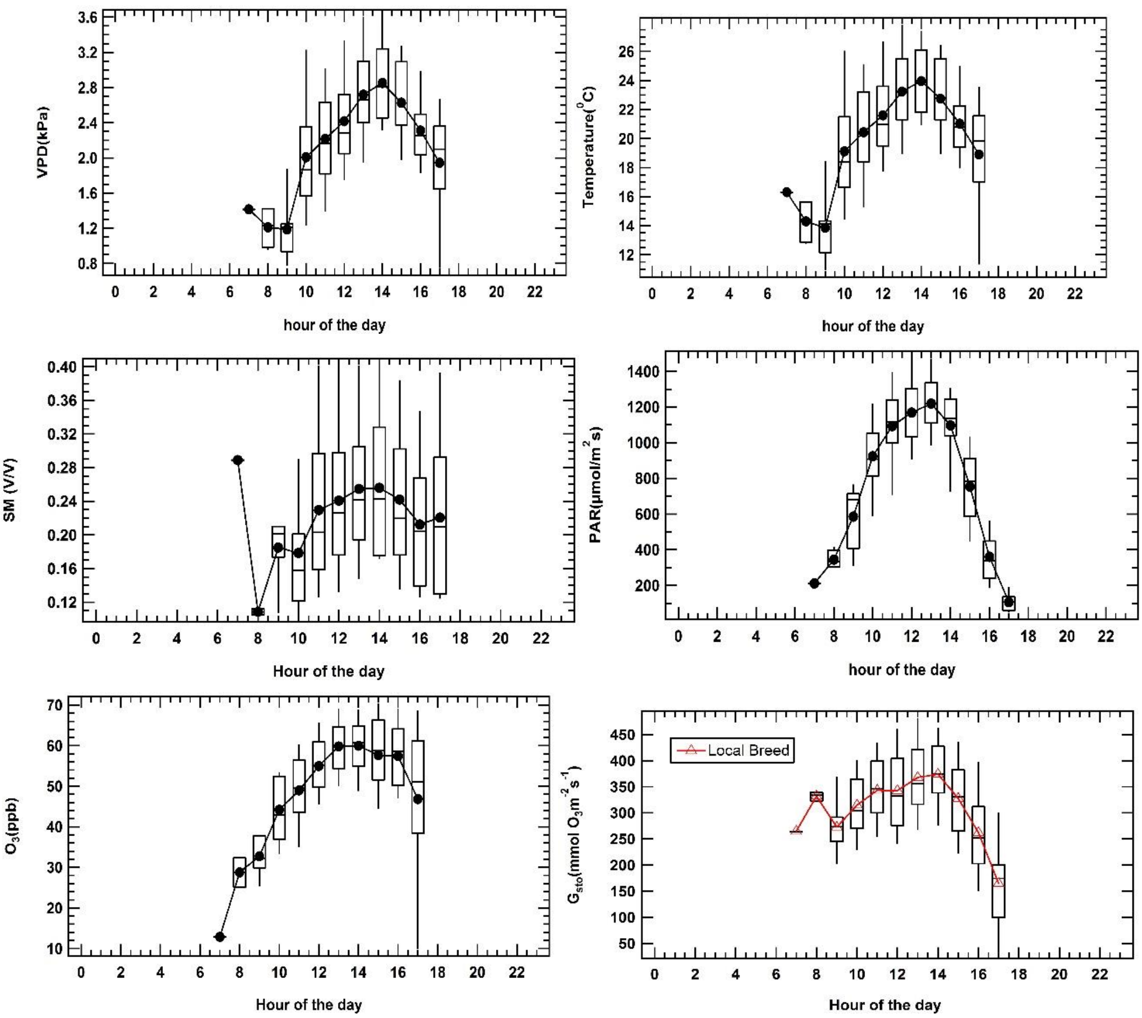


Figure 77: Diel box and whisker plot for the stomatal conductance of Local cultivar along with different environmental parameters for the 2017-18 growing season. All measurements taken during a certain hour of the day during the entire growing season are binned against the start time of the hour. The lower and upper limit of the box represents 75th and 25th percentile and the line in the middle represents the median and the average is marked by a dot. The Whiskers show the 90th and 10th percentile of the data.

In case of local breed, the stomatal conductance is higher during 11:00 to 15:00 hours and showed maximum value at around 15:00 hours. The maximum stomatal conductance for local breed was 620 mmol O_3 m^{-2} s^{-1} There can be higher yield loss at higher temperatures because the optimum temp. for this cultivar is 25^0C.

3.4 Phenology observations

The table below shows different cultivars which shows different growing stages at different temperature sum (T_{sum}). As temperature varies region to region, the cultivars are chosen accordingly.

Cultivar	Emergence T_{sum}	Flag leaf T_{sum}, T_{sum} to Anthesis,	Anthesis T_{sum}	Maturity T_{sum}2018, T_{sum}2017, T_{sum} after Anthesis,
RAJ3765	130 ^{0}C	1030 ^{0}C, -270 ^{0}C	1301 ^{0}C	2470 ^{0}C, 1169 ^{0}C
DBW88	130 ^{0}C	1064 ^{0}C, -306 ^{0}C	1370 ^{0}C	2470 ^{0}C, 1100 ^{0}C
GW322	114 ^{0}C	1164 ^{0}C, -245 ^{0}C	1409 ^{0}C	2470 ^{0}C, 1061^0C
C306	114^0C	1107 ^{0}C, -263 ^{0}C	1370 ^{0}C	2470 ^{0}C, 1100 ^{0}C
Local Breed	145 ^{0}C	1064 ^{0}C, -237 ^{0}C	1301 ^{0}C	2470 ^{0}C, 1169 ^{0}C

Table 1 : T_{sum} daily average required to reach different growth stages for cultivars RAJ3765, DBW88, GW322, C306, Local Breed. Flag leaf maturity temperature sum is shown with respect to anthesis

3.3.1 Comparing the phenology response functions for different cultivars

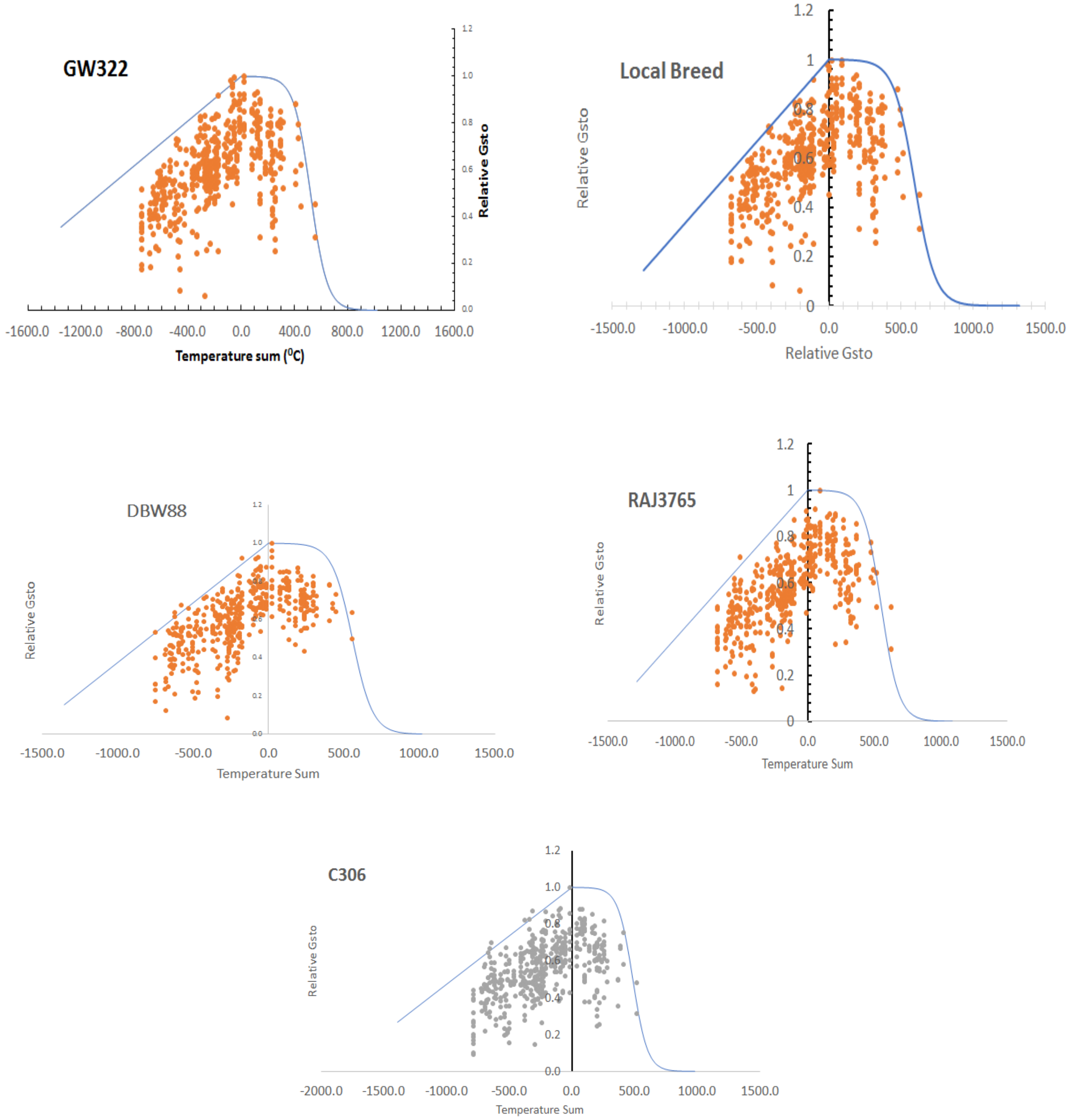


Figure 81 Phenology function for the five wheat cultivars.

The above figure represents how stomatal conductance varies with temperature sum for different cultivars selected. The temperature sum is directly related to phenology of the plant. It is clear from the plots that phenology function increases up to anthesis stage i.e. the stomatal conductance of the leaves increase as they age as long as they remain green and healthy. After Anthesis as the flag leaf turns yellow and biomass is relocated to the grain, the stomatal conductance of the leaf decreases.

For tuning these cultivars two formulation were used. For the first part prior to Anthesis, the linear approach recommended by the mapping manual and reported in Gonzales Fernandez 2010 was used but adapted to reflect the individual cultivars progress along the phenology curve. For the time after Anthesis it was found that the exponential function proposed by the Gonzales Fernandez et al. 2010, more accurately reflects the loss of green healthy leaf area as long as the thermal sum is not capped at 30°C. Instead, if the thermal sum is progressed as per actual measured canopy temperature (even if the same is >34 °C), this function actually reflects the accelerated loss of leaf area due to thermal stress and accomplishes similar outcomes as the thermal stress equation proposed by Asseng et al. 2011. In this case as well, the functions were tuned to reflect the individual cultivars susceptibility to heat stress.

For **RAJ3765** the ascent (=1-(0.2/310) *(-tt))

after anthesis (=1/ (1+0.00025*EXP (0.015*tt))

For **DBW88** the ascent (=1-(0.2/320) *(-tt))

after anthesis (=1/ (1+0.00025*EXP (0.0149*tt))

For **C306** the ascent (=1-(0.2/380) *(-tt))

after anthesis (=1/ (1+0.00025*EXP (0.0171*tt))

For **GW322** the ascent (=1-(0.2/420) *(-tt))

after anthesis (=1/ (1+0.00025*EXP (0.016*tt))

For **Local Breed** the ascent (=1-(0.2/300) *(-tt))

after anthesis (=1/ (1+0.00025*EXP (0.014*tt))

3.5 Comparison of environmental response functions for the four cultivars

3.4.1 Soil moisture function

The figures 14 show how stomatal conductance varies with respect to soil moisture for different cultivars. The soil moisture function is more dependent on soil type, than it is on cultivars and easily biased by statistical artefacts. The wilting point of our soil is approximately 10%. The wilting point is the point where the soil water potential is so negative, that the plant can no longer extract water from the soil. Once the wilting point is reached, the plant closes its stomata to preserve soil moisture and the leaf becomes limp. If water is not replenished to the soil soon, the leaf will start dying from the tip towards the stem. It is therefore, easy to understand, that the data from all the cultivar analysed showed almost similar response function, but the maximum values of soil moisture varies among all the cultivars. This variation does not reflect different behaviour but rather that

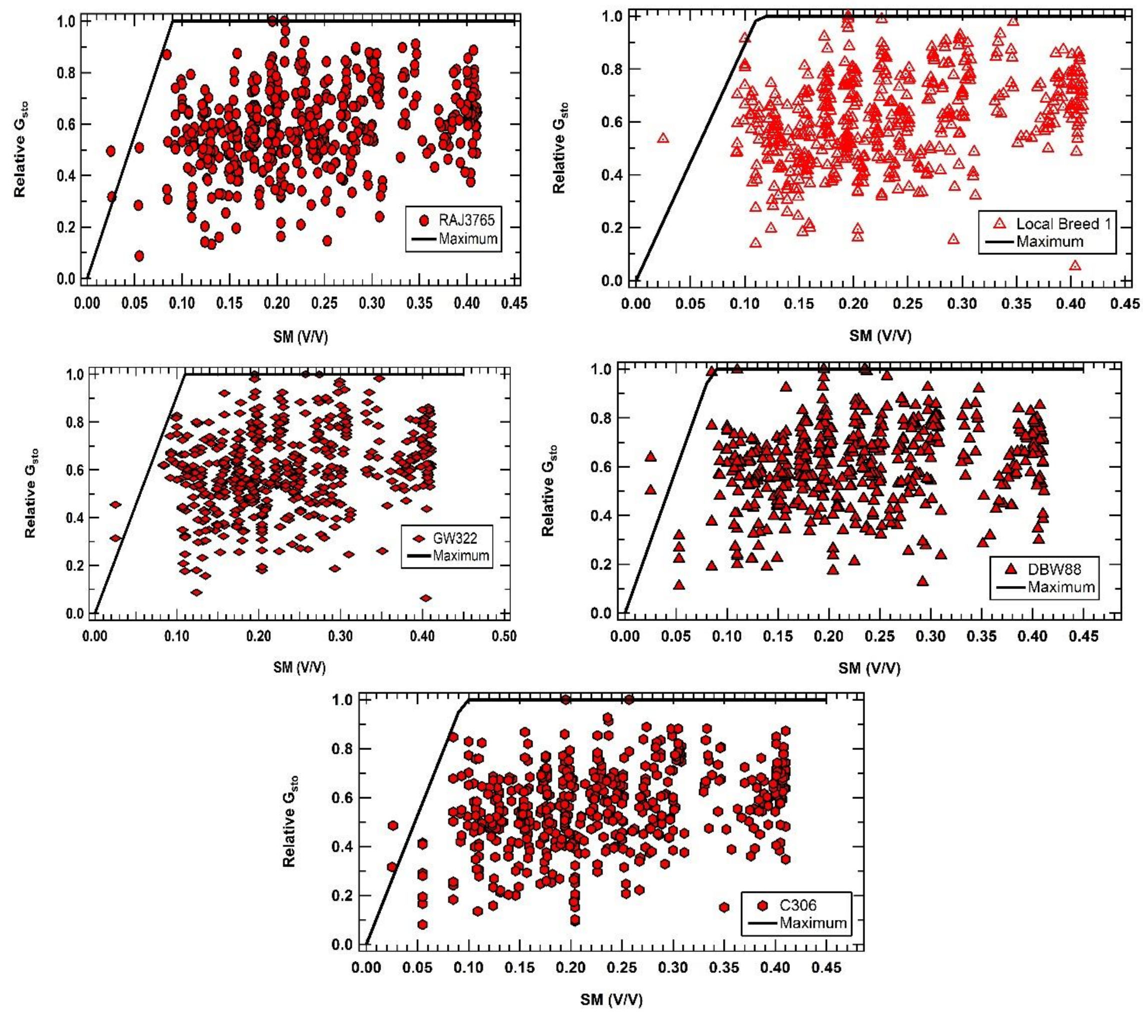


Figure 85 Soil moisture response function for the different wheat cultivars

measurements were taken sequentially and the wilting process (which includes the stomatal closure and dying) progresses with time once the critical soil moisture threshold is crossed. Moreover, due to unevenness in the field, some patches of the field may still have some more moisture, even when the place where the soil moisture sensor is located has already crossed the wilting point.

3.4.2 Photosynthetically Active Radiation (PAR) response function

Figure 15 shows how stomatal conductance (G_{sto}) varies with the light response function for different wheat cultivars. All the cultivars showed similar trend for high PAR values, but the lower PAR values governed by a phenology function 'alpha'. Cultivars at high 'alpha' values keeps their stomata open in intense light conditions whereas stomata remain closed for lower 'alpha' values.

Cultivars C306 has lowest 'alpha' values of 0.0035 and 0.0032 respectively. The highest 'alpha' value is 0.0043 for cultivars DBW88 and GW322. It is clearly visible from the figure 15 that there is a steep increase in the slope for cultivar GW322 and DBW88 shows this cultivar keeps its stomata open even in low light conditions. If the low light conditions are caused by fog and coincide with high RH, then open stomata make a plant more susceptible to fungal infections. Fungal pathogens are more selective towards atmospheric moisture. As per studies the plant pathogens have demonstrated that the moderate temperature and high humidity conditions are liable for fungus infection. (Talley et al., BMC Ecol.2002). However, if the low light conditions are caused by clouds aloft and do not coincide with high moisture at the ground, open stomata may promote greater photosynthesis and better growth. So, therefore, GW322 and DBW88 may be more suitable

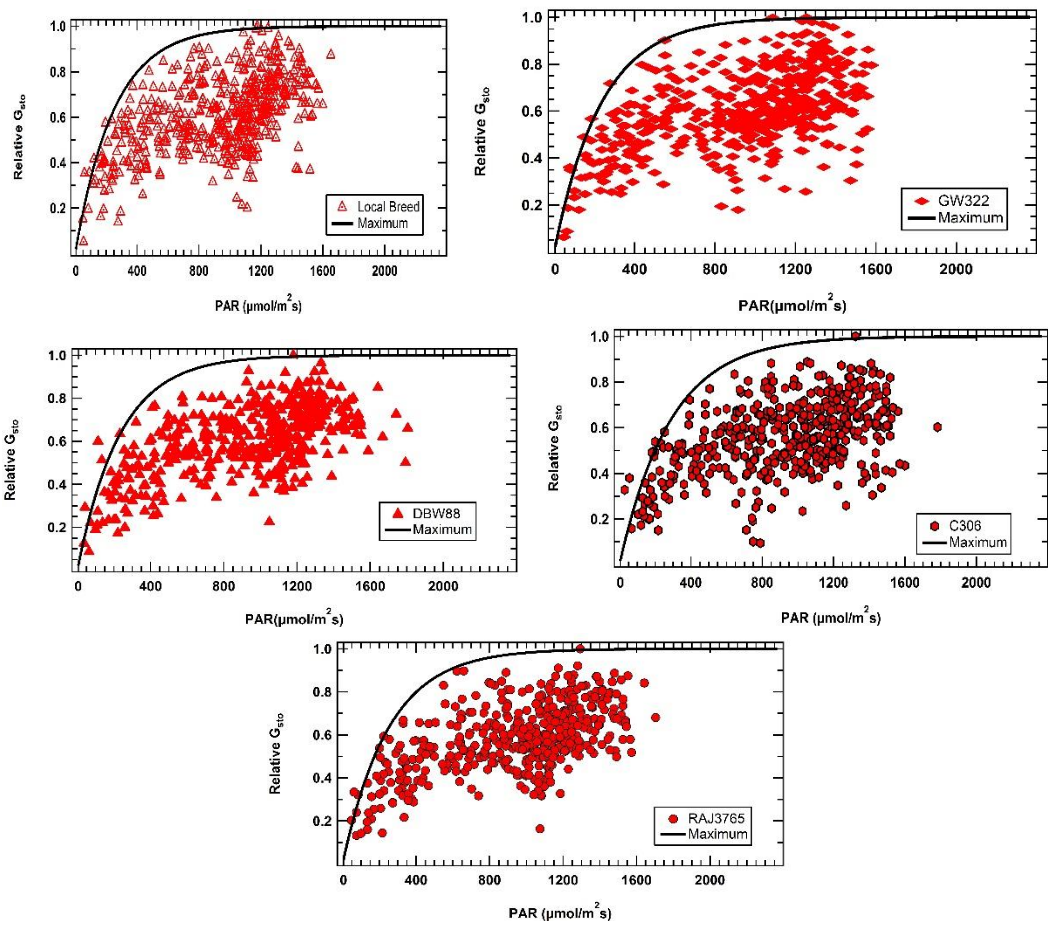


Figure 89 Light response function of the different wheat cultivars.

for rain fed agriculture but less suitable for growth in winter fog affected regions in the IGP.

3.4.3 Temperature response function

Temperature plays an important role not only in controlling the stomatal pore size but also monitoring the enzymatic reactions occurring inside the plant. Figures shows how temperature response function can be used to depict stomatal conductance for the different cultivars. Temperature can adversely effects on both in the photosynthesis and carbon fixation pathways reactions which directly affects the phenology function of these cultivars.

At high temperature conditions more, ozone will be absorbed inside the leaf because stomata are open during day time and there is higher concentration of ozone present in the atmosphere during day time. If stomata are closed during midday or high temperature

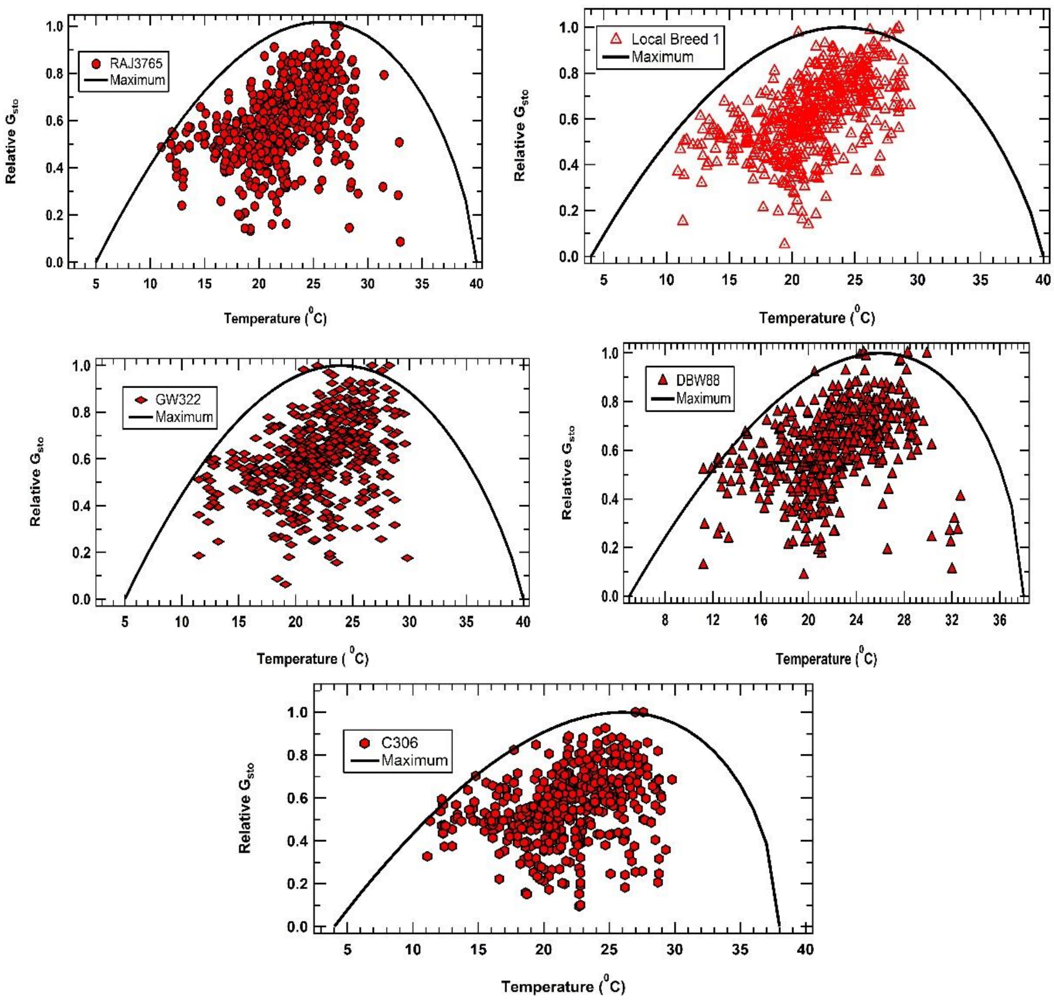


Figure 93 Temperature response function of the four wheat cultivars

conditions, then the plants have to compromise on their photosynthesis activity due to unfavourable conditions but at the same time will take up less ozone.

Cultivars RAJ3765 have the optimum temperature of 28 ^{0}C, Cultivars C306, GW322 and Local Breed have the optimum temperature of 25 ^{0}C and 24 ^{0}C respectively while DBW88 has the optimum temperature of 26 ^{0}C. Hence cultivar RAJ3765 is more prone to ozone damage and crop yield loss because of heat stress.

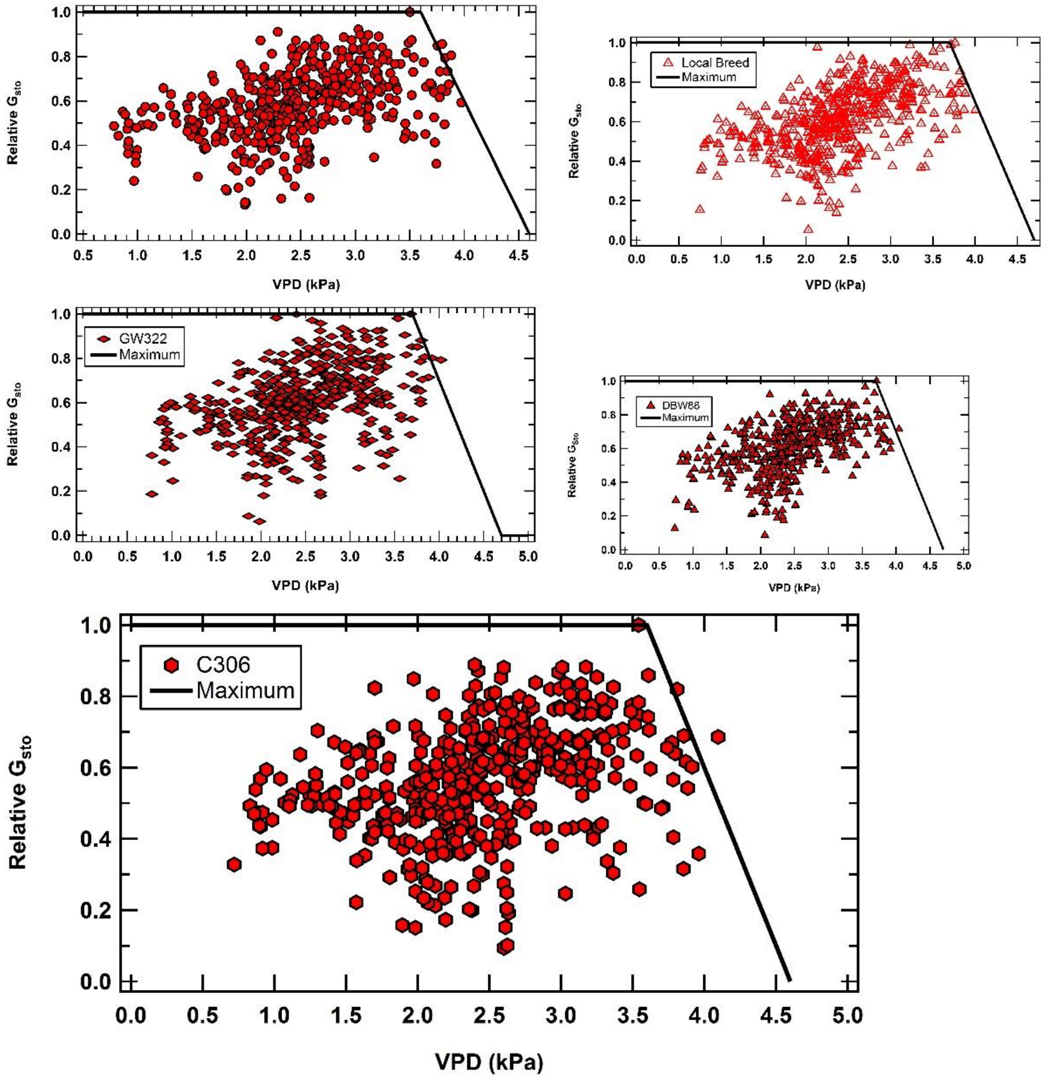


Figure 97 VDP response function of the four wheat cultivars

3.4.4 Vapour pressure deficit (VPD) response function

Figure 16 shows the variation of stomatal conductance with respect to vapour pressure deficit (VPD) which is the measure of dryness/humidity in the air. High VPD suggests drought conditions which are unfavourable for wheat growth because of high temperature and high ozone concentration.

All the six cultivars analysed and showed the almost similar VPD max, which is relatively high, indicating that the plant uses evaporative cooling to bring down temperatures as long as there is sufficient soil moisture.

3.6 Comparison of the implications of the response function of the four cultivars on performance under temperature and drought stress and ozone accumulation within the leaf

RAJ3765

The table below shows the optimized parametrization of the response function for RAJ3765.

	Fphenology		flight	fSM		fVPD		fT		
Parameter	Astart	Aend	A	min	max	min	max	Tmin	Topt	Tmax
Units	˚C days	˚C days	Constant	V/V	V/V	kPa	kPa	˚C	˚C	˚C
RAJ3765	-270	767	0.004	0	0.09	4.5	3.6	5	28	40

Table 5: Different response function parameters for RAJ3765

This cultivar showed an optimum temperature of 28 ^{0}C means maximum stomatal conductance during this time. At Topt plants keeps their stomata open which leads to high accumulation of ozone inside the plant which results in reduce photosynthesis and high relative crop yield loss.

GW322:

The table shows the optimized parametrization of the response functions for GW322.

	Fphenology		flight	fSM		fVPD		fT		
Parameter	Astart	Aend	A	min	max	min	max	Tmin	Topt	Tmax
Units	˚C days	˚C days	Constant	V/V	V/V	kPa	kPa	˚C	˚C	˚C
GW322	-307	724	0.0043	0	0.11	4.8	3.7	5	25	40

Table 6: Different response function parameters for GW322.

This cultivar showed dry conditions by two means. One is high soil moisture function and the other one is VPD max. High values of these two functions indicating less humid conditions means this cultivar needs good irrigated conditions for its proper growth. It takes temperature around 1370 ^{0}C for anthesis.

C306:

The table shows the parameterization of the response functions for C306.

	Fphenology		flight	fSM		fVPD		fT		
Parameter	Astart	Aend	A	min	max	min	max	Tmin	Topt	Tmax
Units	˚C days	˚C days	Constant	V/V	V/V	kPa	kPa	˚C	˚C	˚C
C306	-245	660	0.0035	0	0.095	4.6	3.6	4	25	38

Table 4: Response function parameter for C306

This cultivar showed lower Topt and VPD max relative to another cultivar. Because of lower Topt this cultivar keeps stomata closed under high temperature which prevents transpiration water loss and less ozone accumulation inside the leaves. Due to this no ROS formation which results in proper photosynthesis and less relative yield loss. Because to these factors this cultivar needs high temperature sum of 1408 ^{0}C for Anthesis.

DBW88:

The table shows the optimized parameterization of the response functions for DBW88

	Fphenology		flight	fSM		fVPD		fT		
Parameter	Astart	Aend	A	min	max	min	max	Tmin	Topt	Tmax
Units	˚C days	˚C days	Constant	V/V	V/V	kPa	kPa	˚C	˚C	˚C
DBW88	-263	780	0.0035	0	0.085	4.7	3.7	5	26	38

Table 7: Response function parameter for C306

This cultivar is acceptable for cultivation in those regions which have less humid conditions because it keeps stomata open under low light conditions as represented by low flight value which is 0.0035. As discussed earlier, fungal infections are dominant in low light conditions indicating that this cultivar is more prone to fungal pathogens.

Local Breed:

This cultivar also needs good irrigated condition for growth. It keeps its stomata closed under high solar radiation as suggested by the Topt. This has the capability of providing good yield under high pollution.

	Fphenology		flight	fSM		fVPD		fT		
Parameter	Astart	Aend	A	min	max	min	max	Tmin	Topt	Tmax
Units	˚C days	˚C days	Constant	V/V	V/V	kPa	kPa	˚C	˚C	˚C
Local Breed	-237	821	0.004	0	0.112	4.7	3.7	4	24	40

Table 8: Response function parameters for local breed.

3.7 Maximum stomatal conductance

The table below represents maximum stomatal conductance for different cultivars selected. Higher the stomatal conductance more is the photosynthesis and vice-versa. As discussed earlier, more ozone gets accumulated when stomatal conductance is higher because stomata is opened during this time and this leads to higher yield loss.

Cultivar	G_{max} (mmol O_3 m^{-2} s^{-1})
RAJ3765	720
GW322	550
C306	550
DBW88	570
Local Breed	620

Table 9: Different cultivars and their respective Gmax for ozone

Table 7 shows a comparison of the parameterization for four Indian *T.Aestivum* cultivars with the parameterization reported in the literature from various countries. [1]González-Fernández et al. 2013, [2] González-Fernández et al. 2010, [3]Feng et al. 2012, [4] Pleijel et al., 2007, [5] International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP vegetation) Mapping manual under the United Nation Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP).

Function	Parameter	Units	RAJ3765 India	GW322 India	C306 India	DBW88 India	Local Breed India	Spain[1]	UK cultivars[2]	China[3]	N&W Europe[4]	Mapping manual[5]
f_{phen}	A_{start}	˚C days	-270	-307	-245	-263	-237	-300	-379	-200	-270	-200
	A_{end}	˚C days	767	724	660	780	821	600	518	600	700	700
f_{light}	Alpha	constant	0.004	0.0043	0.0035	0.0035	0.004	0.0105	0.0105	0.0029	0.0105	0.0105
f_{temp}	T_{min}	˚C	5	5	4	5	4	12	9.7	-	12	12
	T_{opt}	˚C	28	25	25	26	24	28	25	-	26	26
	T_{max}	˚C	40	40	38	38	40	39	39.1	-	40	40
f_{VPD}	VPD_{max}	kPa	3.6	3.7	3.6	3.7	3.7	3.2	1.4	1.2	1.2	1.2
	VPD_{min}	kPa	4.5	4.8	4.7	4.7	4.7	4.6	3	5.3	3.2	3.2

Table 10: Comparison of the parameterization for four Indian *T.Aestivum* cultivars with the parameterization reported in the literature from various countries. [1]González-Fernández et al. 2013, [2] González-Fernández et al. 2010, [3]Feng et al. 2012, [4] Pleijel et al., 2007, [5] International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP vegetation) Mapping manual under the United Nation Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP)

Chapter 4

Summary and Conclusion

Ozone is a dynamic pollutant and it is difficult to quantify its effect. As tropospheric ozone is combination of different chemical reactions catalysing by different environmental factors which makes it more difficult to analyse.

Ozone causes damage to crop which results in yield loss. Since photosynthesis is the main source of survival for plants so, ozone cause damage to mesophyll tissue in the plant which blocks the photosynthesis (Grünhage et al., 2012).

Ozone can be quantified by two different means, one is exposure based and other one is stomatal flux based. Stomatal flux based matrics is a more accurate way to quantify the effect of ozone because it gives a clear idea about how much ozone is getting accumulated inside the leaves including all other parameters.

Our study showed that on an average year if the sowing is done on 1st November, we can get better yield as compared to other sowing dates.

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