Canopy temperature and energy balance of irrigated wheat in the hot-arid environment of Sudan

（スーダンの高温乾燥環境における灌漑コムギのキャノピー温度とエネルギー収支）

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A thesis submitted to the United Graduate School of Agricultural Sciences, Tottori University in partial fulfillment of the requirements for the award of Doctoral of Philosophy (Ph.D.) in Global Dryland Science

By

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Dedication

In the scorching embrace of Sudan's hot-arid landscape, this thesis finds its roots and purpose. To those who have accompanied me on this scientific odyssey, I dedicate these pages as a tribute to the relentless pursuit of knowledge and understanding.

To the resilient farmers of Sudan, whose daily toil under the unforgiving sun inspired this exploration. Your commitment to the land and its possibilities fuels the relevance of this research.

To the professors, mentors, and advisors who illuminated my path with their wisdom, expertise, and unwavering support. Your guidance has been the compass in navigating me through the complexities of climate science and agricultural dynamics.

To the land of Sudan itself, with its stark beauty and challenges, serving as both the canvas and crucible for this study. May this work contribute, in however humble a manner, to the sustainable future of agriculture in our arid embrace.

To my family, whose encouragement and understanding have been my shelter in the academic storm. Your belief in my journey has been the wind beneath the wings of this endeavor.

To my friends and colleagues, who have provided laughter, camaraderie, and valuable perspectives. Your presence has made this intellectual odyssey not only challenging but profoundly rewarding.

To the participants and contributors who generously shared their time and experiences, providing the raw material for my research. Your willingness to contribute has enriched the fabric of this work.

As the golden wheat fields sway in Sudan's breeze, may this thesis stand as a testament to the collaborative effort that transcends borders, disciplines, and adversities. May it echo the spirit of inquiry and the resilience of those who strive to unlock the secrets of our natural world.

With profound gratitude,

Almutaz Abdelkarim Abdelfattah Mohammed

Acknowledgment

The completion of this thesis marks the culmination of an incredible journey, one that has been shaped and enriched by the support, guidance, and encouragement of numerous individuals and institutions. As I reflect on this significant milestone, I am profoundly grateful to all those who have played a pivotal role in making this journey possible.

First and foremost, I extend my deepest gratitude to my major supervisor, **Prof. Mitsuru Tsubo**, whose expertise, mentorship, and unwavering support have been the cornerstone of this research endeavor. Your guidance has been instrumental in shaping the trajectory of my academic pursuits, and I am truly fortunate to have had the opportunity to learn under your tutelage.

I would also like to express my sincere appreciation to my co-supervisors, **Prof. Yasunori Kurosaki** and **Prof. Yasuomi Ibaraki**, for their invaluable insights, constructive feedback, and collaborative spirit. Your collective wisdom has added depth and breadth to this work, and I am grateful for the collaborative and enriching environment you have fostered.

The success of this research would not have been possible without the support of the dedicated staff at the Agricultural Research Corporation (ARC), Hydraulics Research Center (HRC), and Arid Land Research Center (ALRC). Your expertise, resources, and commitment to advancing agricultural research have been instrumental in shaping the outcomes of this study.

To my family, whose unwavering support and understanding have been my anchor throughout this endeavor, I express my deepest gratitude. Your encouragement has been the driving force behind my academic pursuits, and I am grateful for the sacrifices you have made to see me reach this milestone.

I express my heartfelt appreciation to my colleagues and friends whose camaraderie, intellectual exchanges, and shared moments of both challenge and triumph have profoundly enriched this academic journey. Your friendship has not only been a source of inspiration but also a testament to the collective strength that propels us forward. I would like to extend a special thank you to the vibrant Sudanese community in Tottori, whose warmth and support have added a unique and invaluable dimension to this experience. Your presence has made a significant impact, turning challenges into opportunities, and transforming triumphs into shared victories.

A special acknowledgment goes to the Japan International Cooperation Agency (JICA) for their unwavering support and investment in my academic journey through the Science and Technology Research Partnership for Sustainable Development (SATREPS) project. Their unwavering support has been instrumental in facilitating my academic journey, allowing me to focus on the research and contribute meaningfully to the field.

Finally, I want to acknowledge the support of everyone—friends, mentors, and well-wishers—who, in various ways, have contributed to this journey. Your encouragement, advice, and belief in my capabilities have been invaluable.

This thesis stands as a collective effort, a reflection of the collaborative spirit that defines the pursuit of knowledge. To each and every individual mentioned and those unmentioned but equally significant, I extend my heartfelt thanks. Your contributions have left an indelible mark on this academic endeavor, and I am grateful for the privilege of standing on the shoulders of such a supportive community.

With sincere appreciation,

Almutaz

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Chapter 1

General Introduction

1.1 Introduction

The issue of climate change is becoming increasingly pressing, with its impact on agriculture being sensed in various regions. Climate change brings about temperature fluctuations, water scarcity, and alterations in growing conditions, making it particularly severe in hot-arid environments. Foley et al. (2005) illustrate the visible impacts of climate change, such as reduced land suitability for farming and decreased crop productivity. Wheat production is particularly at risk, as it is vulnerable to rising global temperatures. (Asseng et al., 2015; Zhao et al., 2017) have quantified the potential impact of climate change on wheat production and projected a 6% reduction in yield with every 1°C increase in global temperature.

The impact is most pronounced in hot and dry environments, where water scarcity and heat waves pose formidable challenges. High-temperature stress accelerates phenological development in wheat as highlighted by Ferris et al., (1998), disrupting crucial growth phases and shortening growing seasons and leading to reduced yields (Akter & Islam, 2017; Asseng et al., 2015; Musa et al., 2021; Shpiler & Blum, 1986; Wheeler & von Braun, 2013; Zhao et al., 2017). The irrigated areas in arid regions such as India and Sudan are the most likely to be affected by climate change (Asseng et al., 2017; Iizumi et al., 2021; Zaveri & B. Lobell, 2019). A similar effect can be observed in rainfed wheat cultivation where Ahmed et al., (2016) reported that a temperature rise of 0 to 5 °C causes a 60% reduction in rainfed wheat grain yield. With the increasing temperatures caused by climate change in hot and dry environments, it becomes increasingly important to grasp how irrigation can modify microclimates through evaporative cooling, this phenomenon of "evaporative cooling" is characterized by several factors, including increased evapotranspiration, shading from dense vegetation, and the presence of water bodies (Kai et al., 1997; Potchter et al., 2008; Taha et al., 1991). which could affect crops grown under irrigation. In this way, heat stress can be mitigated, reducing adverse impacts on crop reproductive processes (Ghafarian et al., 2022; Thiery et al., 2017).

1.2 Background

It is crucial to comprehend how different wheat cultivars react to hot climates to gauge their ability to cope with temperature stress. Various factors, including phenology, physiology, and heat tolerance, can impact a wheat variety's response to elevated temperatures. Previous researches have shown that certain genotypes are more resilience to heat stress, while others display varying degrees of tolerance (Balla et al., 2019; Kumar et al., 2023). Canopy temperature depression (CTD) is used as an indicator to screen wheat genotypes for heat stress tolerance, as wheat cultivars with a cooler canopy grow and yield better in hot environments (Amani et al., 1996; Balota et al., 2007; Fischer et al., 1998; Thakur et al., 2022). However, many meteorological factors such as humidity and wind and morphological characteristics such as plant height and peduncle length affect CTD (Al-Khatib & Paulsen, 1990; Rebetzke et al., 2019). In contrast, standard sensors can be utilized to measure the temperature of the air surrounding the canopy. This valuable data offers researchers and agronomists insight into the microclimates within the canopy, which can significantly affect the crops' physiological processes, stress responses, and overall performance (Zhang et al., 2023). In hot environments with high evaporative demand, the surface temperature of a well-developed canopy with adequate soil moisture is almost entirely dependent on transpiration cooling (Mueller et al., 2016).

Due to the complex factors involved in crop response to the environments, micrometeorological analysis provides a granular examination of energy partitioning in agricultural ecosystems, by studying the energy balance equation which refers to the equilibrium between the energy absorbed and energy released by the canopy, and it can be described by the following equation:

$$Rn = LE + H + G \tag{1}$$

where *Rn* is net radiation, *LE* is latent heat flux, *H* is the sensible heat flux and *G* is the soil heat flux. To quantify components of the energy balance, the Bowen ratio (Bowen, 1926), which represents the relationship between the temperature gradient and the vapor pressure gradient above the crop canopy, is commonly used. The partitioning of energy balance components differs significantly between favorable water conditions and stress conditions (Figure 1.1). According to a study by (Brun et al., 1985), under optimal soil moisture conditions, evapotranspiration (ET) constitutes approximately 92% of net radiation (Rn). Conversely, in dry conditions, ET makes up about 60% of Rn, with sensible heat (H) comprising 30% of Rn. Additionally, this type of analysis uncovers how crops exert a profound influence on local microclimate dynamics. While these findings are important, gaps in our knowledge persist, especially concerning the application of micrometeorological insights to improve wheat cultivation practices in hot-arid regions.

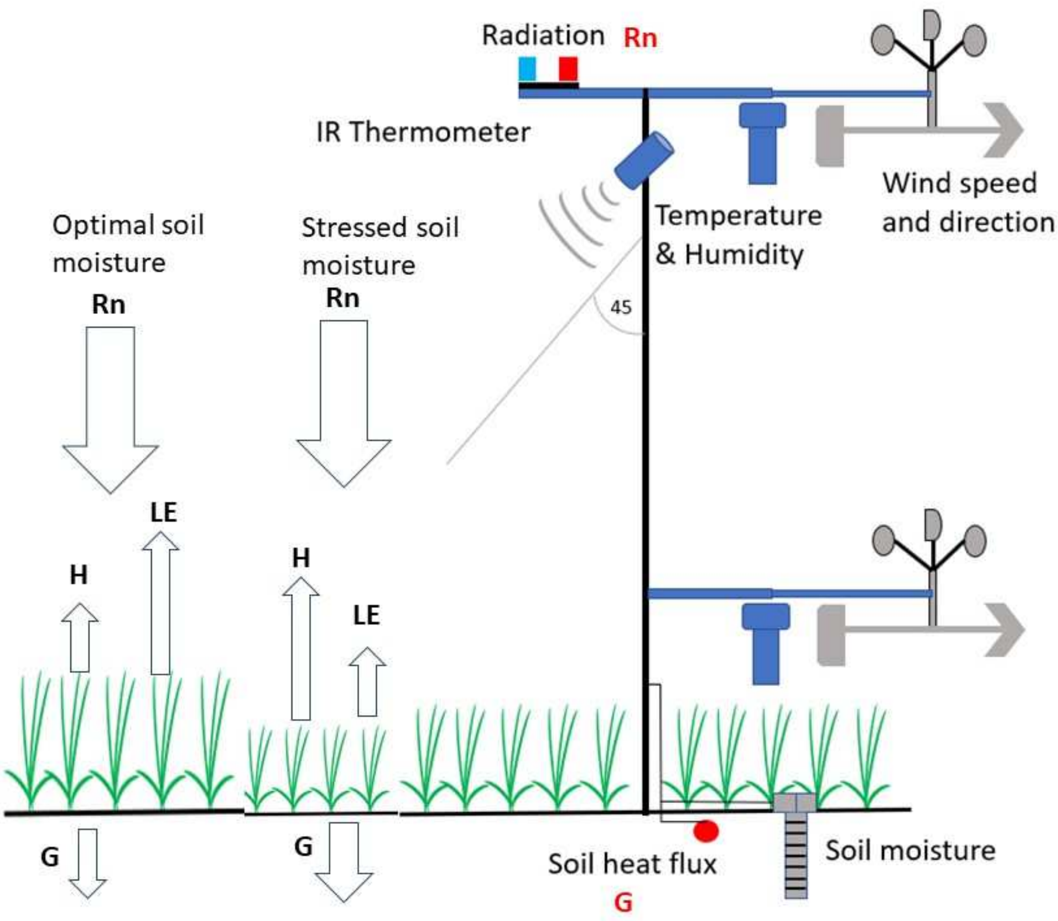

Figure 1.1 Energy partitioning in optimal soil moisture and stressed soil moisture conditions.

1.3 Rationale

Despite significant advancements in the field of micrometeorological analysis, a notable gap persists in integrating these developments to address the unique challenges present in hot-arid environments. While important studies such as (Amani et al., 1996; Brun et al., 1985; Huband & Monteith, 1986a, 1986b; Tanner, 1960) have contributed significantly to our understanding, their focus on individual elements highlights a clear lack of comprehension regarding the holistic interplay between micrometeorological intricacies, irrigation dynamics, and varietal adaptations, particularly within the context of wheat cultivation in hot-arid environments. This research gap is important in understanding how variations in energy balance components, canopy temperature, and wheat cultivars affect the overall productivity and health of wheat crops facing harsh environmental conditions.

The complex relationship between wheat cultivation and microclimates in hot-arid environments has gained heightened significance in the context of climate change and the urgent need to ensure global food security. Understanding the microclimate is crucial for evaluating whether the atmospheric conditions are suitable for crops (Gardner et al., 2021). It involves analyzing how the energy is distributed between sensible heat and latent heat in crop fields. Additionally, plant growth conditions and environment differ between controlled environment research and field conditions (Poorter et al., 2016). Therefore, studying microclimates can help us comprehend how vegetation affects the local climate by regulating energy exchanges which permits researchers to determine the relative contributions of sensible heat flux and latent heat flux towards the overall energy balance of the wheat crop. Despite advancements in micrometeorological data collection, the micrometeorological approach is rarely used to differentiate cultivar variances in hot environments.

The role of micrometeorology cannot be overstated in its influence on the physiological development of crops. Previous research has demonstrated that even small temperature fluctuations at a microscale can have a significant effect on crop response. It is therefore critical to investigate the micrometeorological aspects that impact how wheat responds to heat stress. While earlier studies have provided valuable insights into this subject, a cohesive framework that synthesizes these multifaceted factors into a comprehensive understanding is still necessary.

Drawing upon the insights gained from the existing knowledge, our refined hypothesis proposes that there is no evidence to suggest that different types of wheat have specific adaptations that help them cope with high-temperature stress. Additionally, irrigation does not play a significant role in shaping the thermal environment of wheat fields or influencing wheat's adaptive responses to high temperatures. Finally, the interplay between wheat cultivars, irrigation, and microclimatic conditions does not significantly contribute to the resilience and of wheat crops in the hot environment of Sudan.

1.4 Objectives of the Thesis

Wheat cultivation in Sudan has a long history, particularly in the Northern State. However, due to the increasing production costs and limited land availability, the practice has spread southward. This expansion has necessitated the incorporation of irrigated schemes in central (Gezira scheme) and eastern Sudan (New Halfa scheme) to meet the growing demand (O.A.A, 1994). The purpose of this thesis is to advance our understanding of microclimates in irrigated wheat cultivation in the hot-arid environments, focusing on the following two objectives: (1) to investigate cultivar differences in the canopy temperature of irrigated wheat, and (2) to characterize the energy balance of wheat grown under irrigation.

The methodology employed in this thesis includes extensive micrometeorological measurements from wheat fields during the growing seasons, such as energy balance components (net radiation and soil heat flux), windspeed, temperature, humidity, and soil moisture, then Bowen ratio analysis was conducted to analyze energy balance.

This thesis is structured to provide comprehensive insights into wheat cultivation in hot-arid environments. Chapter 2 delves into a micrometeorological comparison of canopy temperatures between two wheat cultivars grown under irrigation. Chapter 3 focuses on evaluating the energy balance in irrigated wheat fields. Finally, Chapter 4 offers a general conclusion that synthesizes the findings and their implications for sustainable agricultural practices and avenues for future research.

Chapter 2

2 Micrometeorological Comparison of Canopy Temperature between Two Wheat Cultivars

2.1 Introduction

Wheat (Triticum aestivum L.) is strongly affected by climate change, with yields projected to decrease by 6% for every 1 °C increase in global temperature (Asseng et al., 2015; Zhao et al., 2017). The most obvious effect of high temperatures on wheat is accelerated phenological development, resulting in shorter growing seasons and reduced yields (Akter & Islam, 2017; Shpiler & Blum, 1986). Among the world's wheat-producing regions, the effects of climate change are expected to be particularly severe in irrigated areas in arid regions such as India and Sudan (Asseng et al., 2017; Iizumi et al., 2021; Zaveri & B. Lobell, 2019). In these regions. Canopy temperature depression (CTD)—the difference between air temperature (Ta) and radiometric canopy surface temperature (Ts) at standard (2 m) height, viz., CTD = Ta − Ts—is used as an indicator to screen wheat genotypes for heat stress tolerance, as wheat cultivars with a cooler canopy grow and yield better in hot environments (Amani et al., 1996; Balota et al., 2007; Fischer et al., 1998; Thakur et al., 2022). However, many meteorological factors such as humidity and wind, and morphological characteristics such as plant height and peduncle length affect CTD (Al-Khatib & Paulsen, 1990; Rebetzke et al., 2019).

Accurately measuring crop CTD is essential for identifying heat and drought-resistant wheat varieties. A range of techniques are employed for measuring CTD, including handheld infrared thermometers (Amani et al., 1996; Deery et al., 2019; Lepekhov, 2022; Neukam et al., 2016; Thakur et al., 2022), thermal cameras (Anderegg et al., 2021; Grant et al., 2006), and increasingly, thermal imaging (Das et al., 2021). These methods are typically employed in clear weather conditions during the afternoon, and they directly assess the radiative heat emitted by the canopy (Huband & Monteith, 1986a), providing insights into drought stress (Blum et al., 1982; Jackson et al., 1981; Lepekhov, 2022). Conversely, air temperature at the canopy level (Tc) is derived from standard sensors in the surrounding air, offering an overview of the air temperature around the canopy. This information aids researchers and agronomists in understanding microclimates within the canopy, influencing plant physiology, stress responses, and overall crop performance (Zhang et al., 2023). Analyzing these temperatures facilitates the identification of heat stress patterns and guides the implementation of beneficial agronomic practices, such as optimizing irrigation (O'Shaughnessy & Evett, 2010) and heat stress mitigation techniques. This enhances crop management for improved yield in hot environments.

Since wheat is adapted to cool environments, high temperatures are detrimental. At the individual plant scale, they decrease photosynthesis, thus reducing transpiration, which is positively associated with stomatal conductance, which in turn is highly affected by the vapor pressure deficit (VPD) of the atmosphere (Balota et al., 2007; Feng et al., 2014; Sharma et al., 2015; Steiner & Hatfield, 2008). At the field scale, the transpiration–VPD relationship is complicated by air movement. Unless water vapor moves from the evaporating canopy surface into the atmosphere, it accumulates near the canopy surface, and the low VPD suppresses transpiration (Steiner & Hatfield, 2008). When the air is dry just above a well-watered canopy, the high VPD increases stomatal conductance, letting more water vapor be released from the canopy surface into the atmosphere. This behavior of water movement in the soil–plant–atmosphere continuum occurs along with the evaporative cooling of the canopy. In hot environments with high evaporative demand, the surface temperature of a well-developed canopy with adequate soil moisture is almost entirely dependent on transpiration cooling (Mueller et al., 2016). Decreasing transpiration under elevated VPD has been proposed as a crucial trait for drought tolerance. This approach aims to mitigate excessive water loss, prevent hydraulic failure, and enhance overall water use efficiency (Eyland et al., 2022; Medina et al., 2019).

At high temperatures, especially during grain filling, wheat yields are higher at higher VPD (Gourdji et al., 2013) as a result of the crop's response to atmospheric water vapor pressure (VP) throughout the growing season. The crop's sensitivity to VP can be characterized by the above-canopy vapor pressure gradient (VPG)—the difference between VP at standard height (VPa) and that at canopy level (VPc), viz., VPG = VPa − VPc. According to the Monin–Obukhov similarity theory of heat, water vapor and mass fluxes (Monin & Obukhov, 1954), the relationship between air temperature and VP can be interpreted as the association of the above-canopy air temperature gradient (ATG)—the difference between Ta and Tc, viz., ATG = Ta − Tc—with VPG. This relationship with respect to the canopy surface has been studied in specific wheat cultivars (Dugas et al., 1991; Huband & Monteith, 1986a) but not compared between cultivars. Moreover, these micrometeorological parameters have been reported mainly for daytime and specific growth stages. To fully understand the ATG–VPG relationship for cultivar comparison, diurnal changes in Tc and VPc need to be measured throughout the growing season. In addition, as Tc and Ts differ in theory, their relationship needs to be investigated.

The Gezira Scheme in Sudan is one of the hottest wheat-growing areas in the world, and its irrigated wheat yields are projected to decrease under climate warming (Iizumi et al., 2021; Musa et al., 2021). Adaptation to climate change requires accelerated crop improvement for heat tolerance in controlled environments (Atlin et al., 2017). However, there is a lack of information on microclimates of irrigated wheat in hot environments to explain crop responses to high temperatures. Therefore, the main objective of this study was to investigate cultivar differences in the canopy temperature of irrigated wheat using a micrometeorological method. The specific objectives were (i) to compare CTD and ATG of two cultivars contrasting in growth habit and (ii) to determine the relationship between ATG and VPG. The effect of wind on this relationship is discussed in relation to the temperature–humidity–wind relationship above the canopy. The micrometeorological approach has seldom been used to identify cultivar differences, and this study is the first to use it to compare canopy temperature between cultivars in a very hot wheat-growing area.

2.2 Materials and Methods

2.2.1 Field experiments

Field experiments were conducted during the dry season of 2020–21 at the Gezira Re-search Station of the Agricultural Research Corporation, Sudan (14.38°N, 33.50°E), within the Gezira Scheme in the arid climate zone (Figure 2.1). The climate is characterized by low annual precipitation (about 300 mm) from July to September and almost nil during the wheat growing season (November–March) (Elagib & Mansell, 2000). The temperatures are lowest from November to February, and the monthly average ranges between 23.6 °C in the coldest months and 33.1 °C in the warmest months (Elagib & Mansell, 2000). The soil is classified as Vertisol, with a clay content of 50%–60% (Herve, 1990).

The experiments in two adjacent fields were designed to compare two high-yielding heat-tolerant wheat cultivars, i.e., Bohaine and Imam, which are the most common commercial cultivars grown in dry environments in Sudan. Bohaine is a fast-maturing cultivar with a fully erect growth habit, whereas Imam is a later-maturing cultivar with a semi-prostrate growth habit (Tahir et al., 2017). Each field measured 180 m long by 70 m wide (1.26 ha), aligned north–south; Bohaine was sown on 26 November and Imam on 6 December 2020 at 120 kg ha−1 in north–south rows 0.2 m apart. The fields were flood-irrigated immediately after sowing and every 8 to 13 days until 1 March 2021, Imam 10 times and Bohaine 9 times. The fields received the same type and amount of fertilizers: 25 kg N ha−1 and 28 kg P ha−1 in the form of diammonium phosphate before sowing and 56 kg N ha−1 of urea split-applied at the second and fourth irrigations. Each field had an automatic micrometeorological station installed in the southern part on 13 January 2021.

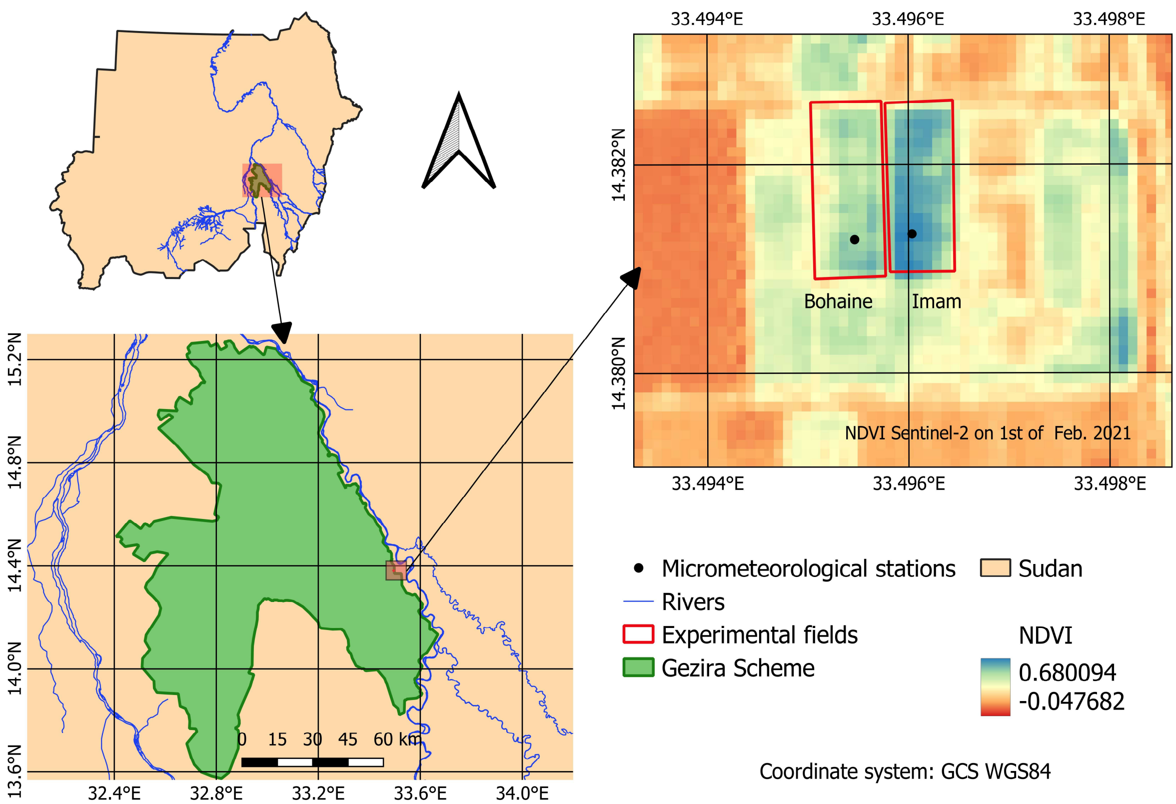

Figure 2.1 Location of experimental fields in the study area, the Gezira Scheme (Sudan). The fields are indicated on a map of Sentinel-2 satellite-based NDVI on 1 February 2021.

2.2.2 Data collection and calculation

Plant height was measured four times (vegetative, heading, post-anthesis and grain-filling stages): on 21 January, 31 January, 14 February, and 28 February 2021 for Imam and 21 January, 1 February, 15 February, and 28 February 2021 for Bohaine. At each measurement, three quadrats consisting of three 1.11-m-long rows (ca. 1 m2) were selected on the south side of the micrometeorological station in each field. Ten plants were randomly sampled in each quadrat and values were averaged for statistical analysis. The Normalized Difference Vegetation Index (NDVI) of each field was calculated as a proxy for the leaf area index (LAI) and aboveground biomass (Cabrera-Bosquet et al., 2011; Tan et al., 2020) from near-infrared and red radiance reflectance data from the European Space Agency Sentinel-2 satellite at a spatial resolution of 10 m × 10 m (https://sentinels.copernicus.eu/web/sentinel/home). Gridded NDVI data within each field were averaged over the area of fields for each satellite image for comparison. Heading date was recorded as when 50% of the plants had the base of the spikes emerging from the flag leaf.

Temperature, humidity, and wind data were collected in the center of the field with more than 130 m green fetch towards the north direction, at two heights with HMP155 probes (Vaisala Oyj, Vantaa, Finland) protected by a forced-ventilation shelter and 03002-47A anemometers (R. M. Young Co., MI, USA). The upper sensors were fixed at 2 m above the ground, and the lower sensors were periodically adjusted to 0.05–0.1 m above the canopy surface. To measure canopy surface temperatures (Ts), an SI-411 infrared radiometer (Apogee Instruments, Inc.,Logan, UT, USA) capable of monitoring temperatures over a canopy surface area of 8.4 m2 was fixed 2 m above the ground, tilted 45° down to the vertical mounting pole of the station and perpendicular to the western crop row. Measurement intervals were 1 min for Ta, Tc, Ts, and relative humidity (RH) and 1 s for wind speed and direction (WS and WD). Data averaged every 10 min was recorded on a CR1000X datalogger (Campbell Scientific, Inc., Logan, UT, USA).

Hourly Ta, Tc, Ts, and WS at 2-meter height (WSa) and canopy level (WSc) were calculated by averaging 10-min data for each hour of the 24-h day. We calculated 10-minutes-averaged VPa and VPc from RH and air temperature according to (Allen et al., 1998) and averaged them for each hour. WD at 2-m height (WDa) and canopy level (WDc) was used to determine the fetch requirement for the micrometeorological measurements. We calculated the percentages of the WD data with WS > 0.5 m s−1 (the threshold speed at which the vane began to move) between north-northwest and north-northeast to ensure sufficient distance from the northern end of the field to the station with respect to the wind direction.

2.2.3 Statistical analysis

Plant height was compared between cultivars by unpaired t-test to ensure the same conditions necessary for micrometeorological comparisons, i.e., the same height of canopy surface between fields. CTD and ATG were analyzed for each of three growth periods: 21 to 30 January (I), 31 January to 14 February (II), and 15 to 28 February (III), which were determined from the dates of plant height measurements. In each hour of the 24-h day in each growth period, CTD and ATG were compared between fields by paired t-test. To clarify the relationship between ATG and VPG in each growth period, we used linear regression analysis, dividing the data into daytime (from hours 7 to 18) and nighttime (from hours 19 to 6) on the basis of latitude. Pearson's correlation analysis was performed to determine the relationship between Ts and Tc during all periods. All statistical analyses were performed in R software (R Core Team, 2023).

2.3 Results

2.3.1 Crop data

There were no significant differences in plant height between the Bohaine and Imam fields on any measurement date ($P > 0.05$; Figure 2.2). However, NDVI was significantly higher in Imam on all dates. Periods I, II, and III corresponded respectively to the late vegetative stage, heading to early grain filling, and mid to late grain filling in Imam, and to the late vegetative stage to heading, early to mid-grain filling, and late grain filling in Bohaine.

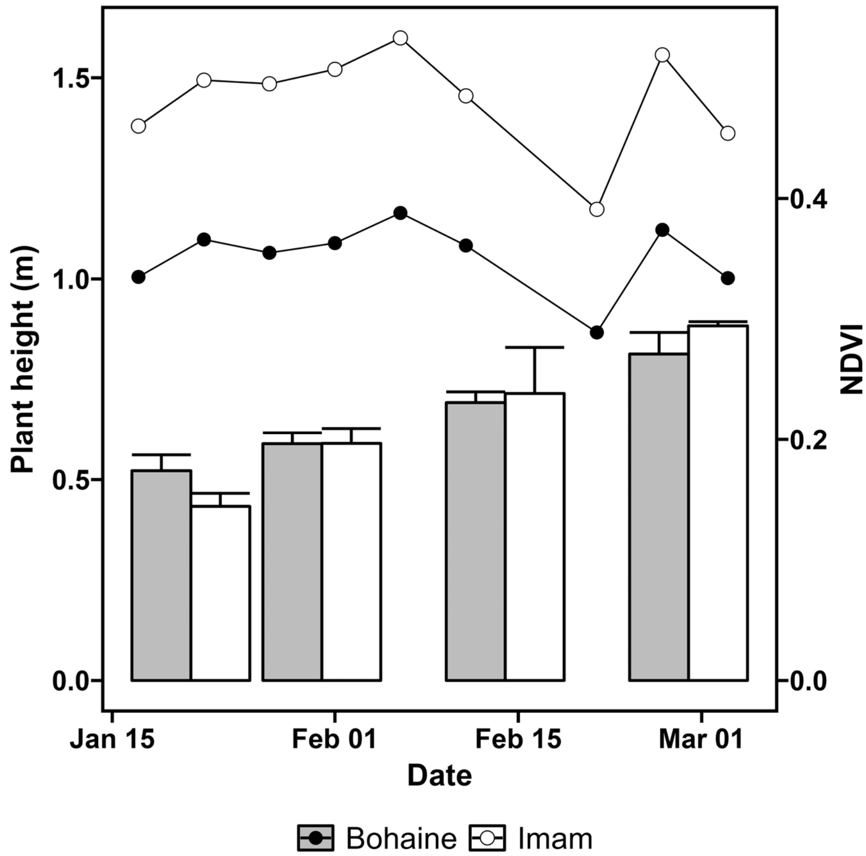

Figure 2.2 Seasonal changes in plant height (bars, mean ± SD) and NDVI (points) of wheat cultivars Imam and Bohaine.

2.3.2 Micrometeorological data

During period I, Ta was lowest around sunrise and highest around early afternoon (Figure 2.3). During periods I–III, the maximum Ta was 37.2 °C in the Bohaine field and 37.3 °C in the Imam field, and the maximum Tc was 36.1 °C and 34.5 °C, respectively. Tc was positively correlated with Ts and was higher than Ts, and the relationship did not differ between daytime and nighttime (Figure 2.4). Both VPa and VPc increased from early morning to around noon, and then decreased until late afternoon and remained low until early the next morning (Figure 2.3). The maximum VPa during periods I–III was 1.9 kPa in both fields, which was lower than the maximum VPc (2.3 kPa in Bohaine field, 2.6 kPa in Imam field).

Wind speeds were higher during the daytime than during the nighttime (Figure 2.3), with a period I–III average WSa of 3.2 m s−1 in the daytime and 1.7 m s−1 in the nighttime in both fields. The average WSc was 1.3 m s−1 in the daytime and 0.4 m s−1 in the nighttime in the Imam field and

1.6 and 0.5 m s−1, respectively, in the Bohaine field. The period I–III nighttime wind direction at 2.0 m (WDa) was northerly 70.8% of the time in the Bohaine field and 65.7% of the time in the Imam field; and that at canopy height (WDc) 71.0% of the time in the Bohaine field and 73.7% in the Imam field. In contrast, the daytime WDa was northerly only 31.7% and 43.6% of the time, and the daytime WDc only 44.3% and 59.4% of the time, respectively (data not shown).

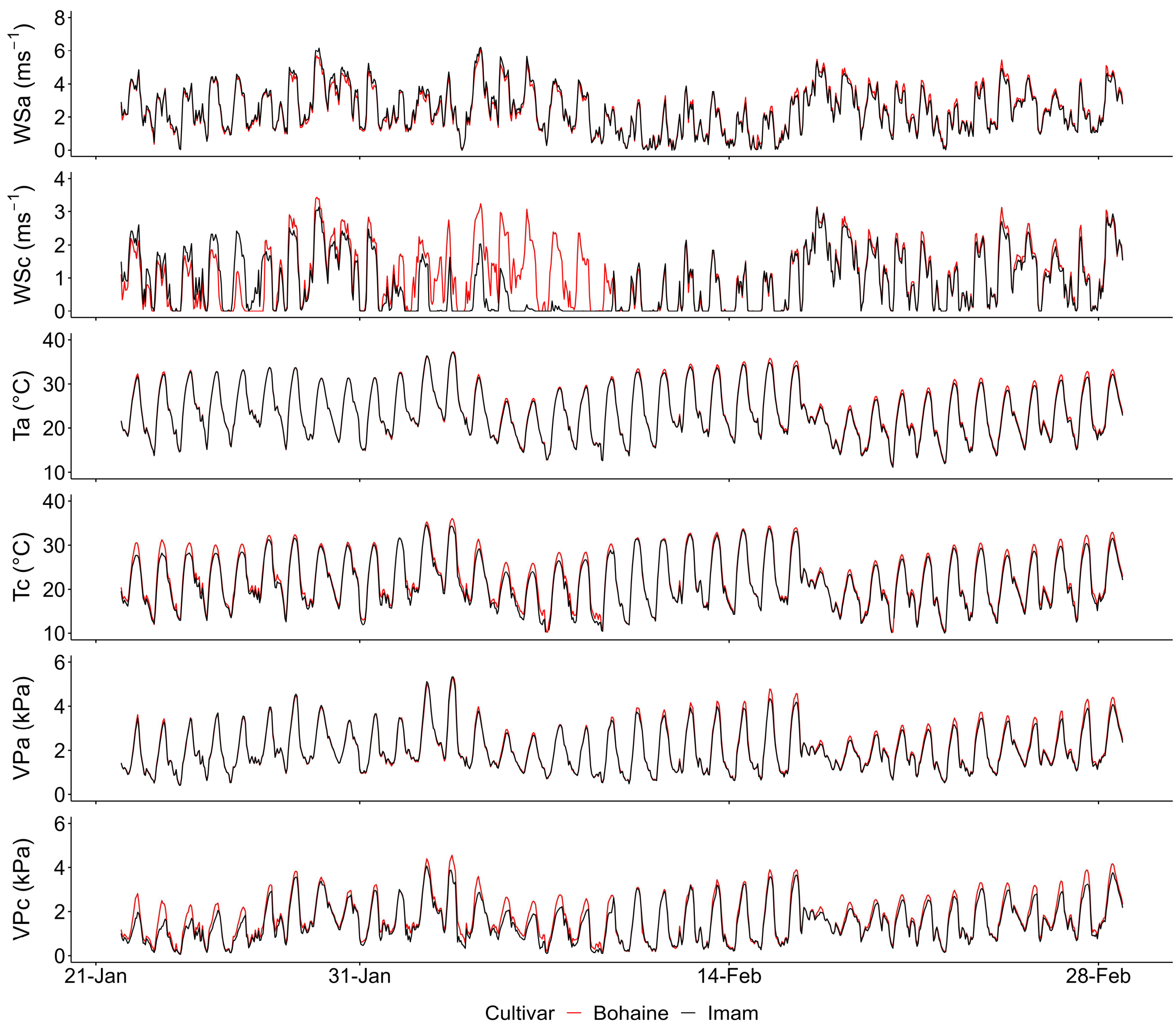

Figure 2.3 Seasonal changes in wind speed (WS), air temperature (T), and atmospheric water vapor pressure (VP) at 2-m height (“a”) and canopy level (“c”) in irrigated fields of wheat cultivars Imam and Bohaine.

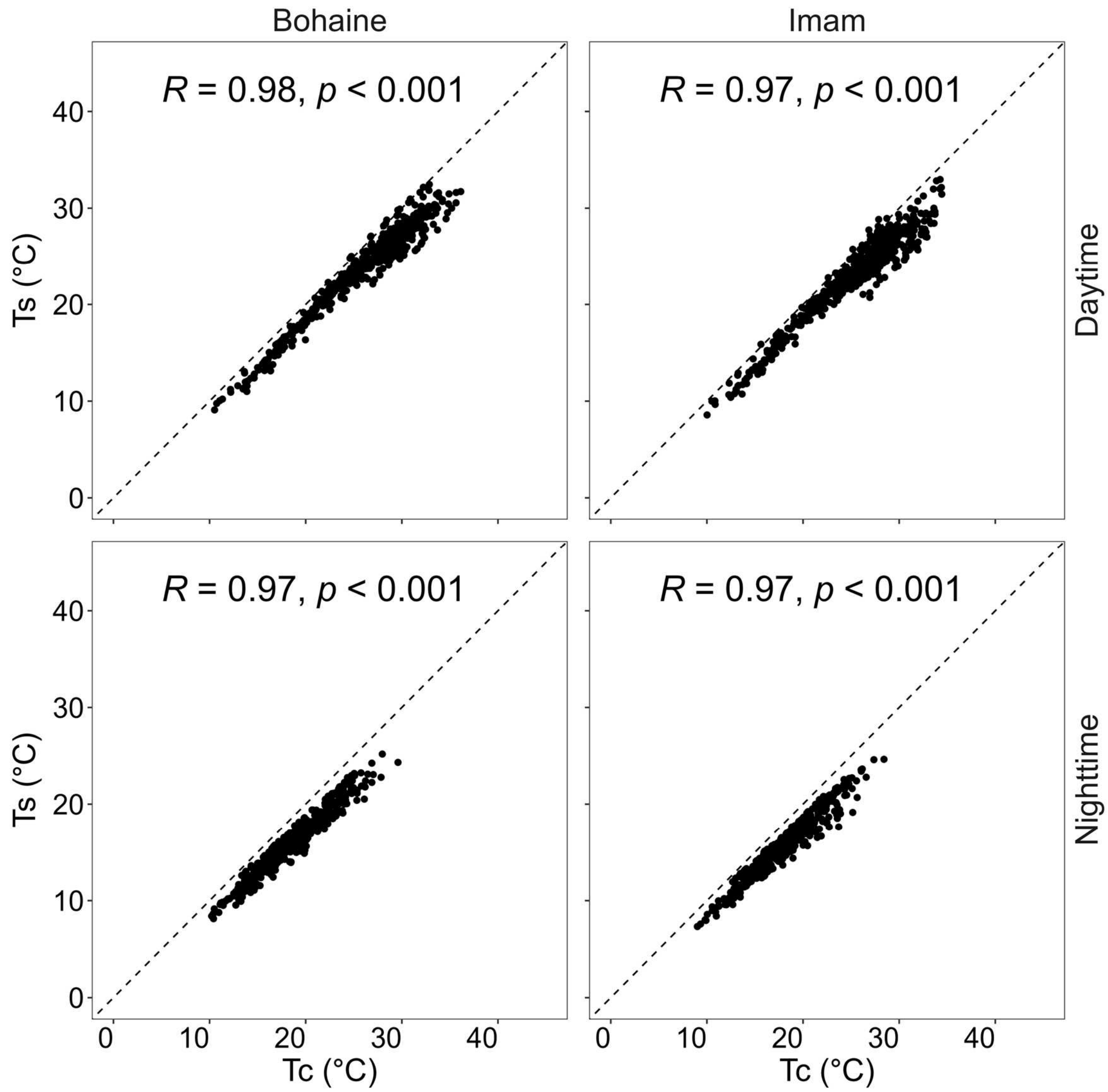

Figure 2.4 Relationships between canopy surface temperature (Ts) and air temperature at canopy level (Tc) during daytime (hours 7 to 18 of the 24-h day) and nighttime (hours 19 to 6) in irrigated fields of wheat cultivars Imam and Bohaine from the late vegetative to late reproductive stages (21 January to 28 February 2021).

2.3.3 Comparison of CTD and ATG between cultivars

The hourly average CTD in period I was significantly larger in the Imam field than in the Bohaine field during the nighttime (from hours 19 to 3) but not during most hours of the daytime (Figure 2.5). That in period II differed between fields from hours 14 to 8. That in period III differed during most hours of the day. In the Bohaine field, the maximum CTD was 6.5 °C in hour 17 in period I, 6.5 °C in hour 19 in period II, and 4.7 °C in hour 19 in period III. In the Imam field, it was 6.4 °C, 7.2 °C and 5.0 °C, respectively, during the same hours.

The hourly average ATG was larger in the Imam field than in the Bohaine field during all hours in period I and during most hours in periods II and III (Figure 2.5). The maximum ATG was 2.4 °C in hour 21 in period I, 2.6 °C in hour 19 in period II, and 1.9 °C in hour 20 in period III in the Bohaine field, and 3.4 °C in hour 16 in period I, 3.4 °C in hour 20 in period II, and 1.9 °C in hour 20 in period III in the Imam field.

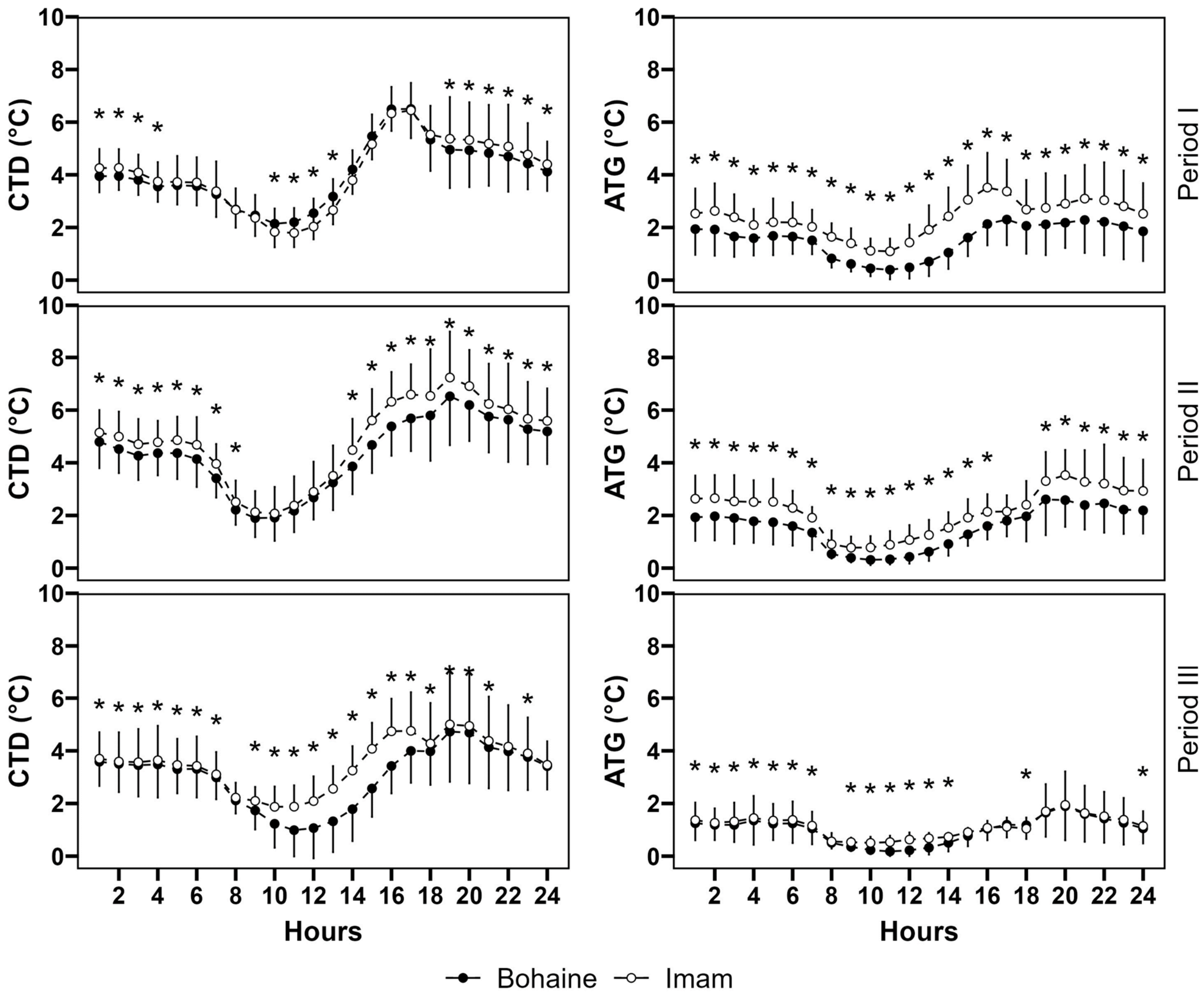

Figure 2.5 Diurnal changes in canopy temperature depression (CTD) and above-canopy air temperature gradient (ATG) in irrigated fields of wheat cultivars Imam and Bohaine during periods I (21−30 January 2021), II (31 January – 14 February), and III (15−28 February). Points are means and bars are SD. *Significant difference at P ≤ 0.05.

2.3.4 Relationship between ATG and VPG

Daytime ATG was correlated negatively with VPG in both fields during all periods (R2 = 0.02 to 0.30), except in the Imam field in period III (Figure 2.6). The relationship was moderate in period

I and weak in period II. The nighttime relationship between ATG and VPG was stronger in both fields during all periods (R2 = 0.73 to 0.90; Figure 2.7).

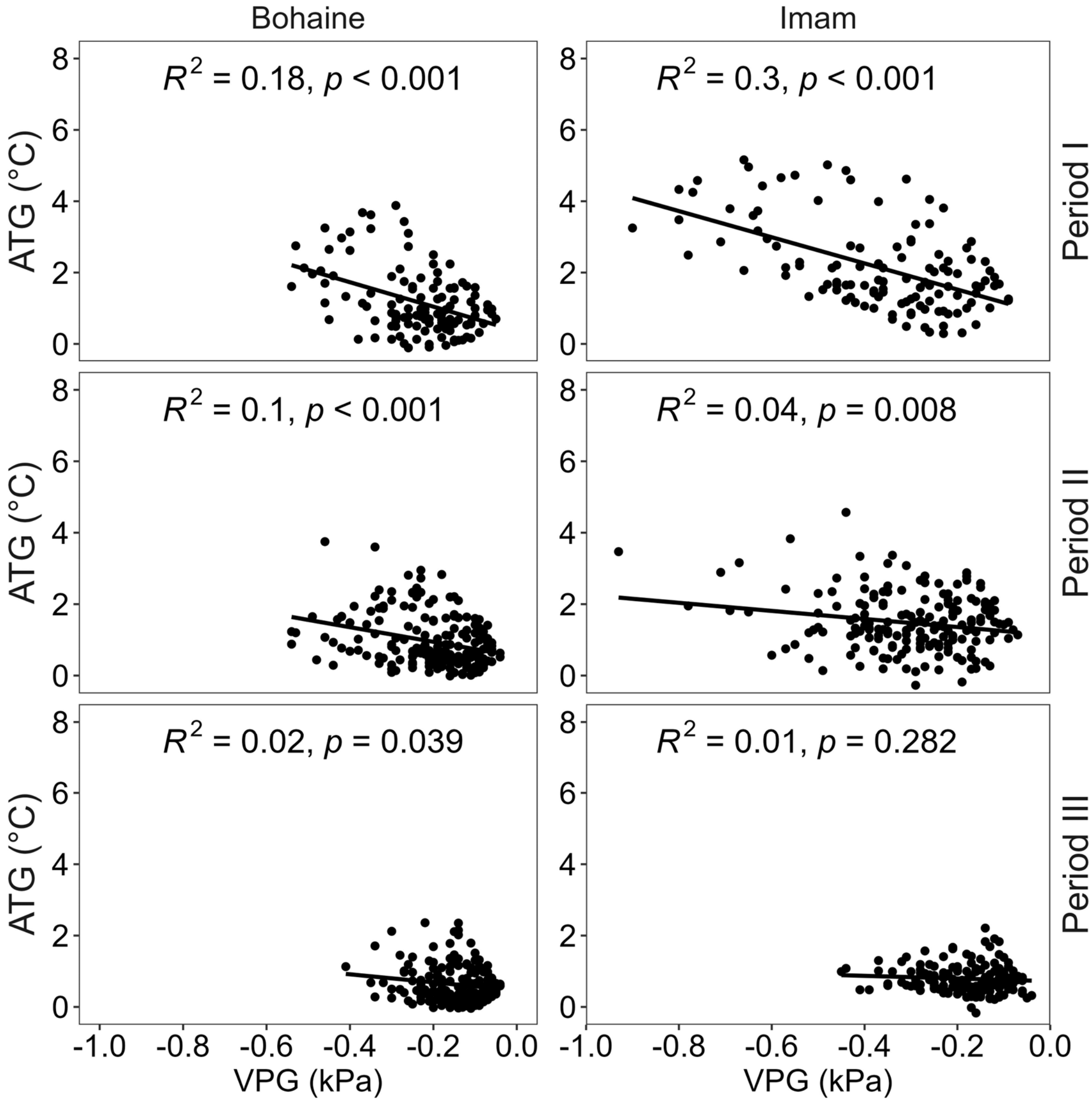

Figure 2.6 Relationships between above-canopy air temperature gradient (ATG) and above-canopy water vapor pressure gradient (VPG) during daytime (hours 7 to 18 of the 24-h day) in ir-rigated fields of wheat cultivars Imam and Bohaine in periods I (21−30 January 2021), II (31 Janu-ary − 14 February), and III (15−28 February).

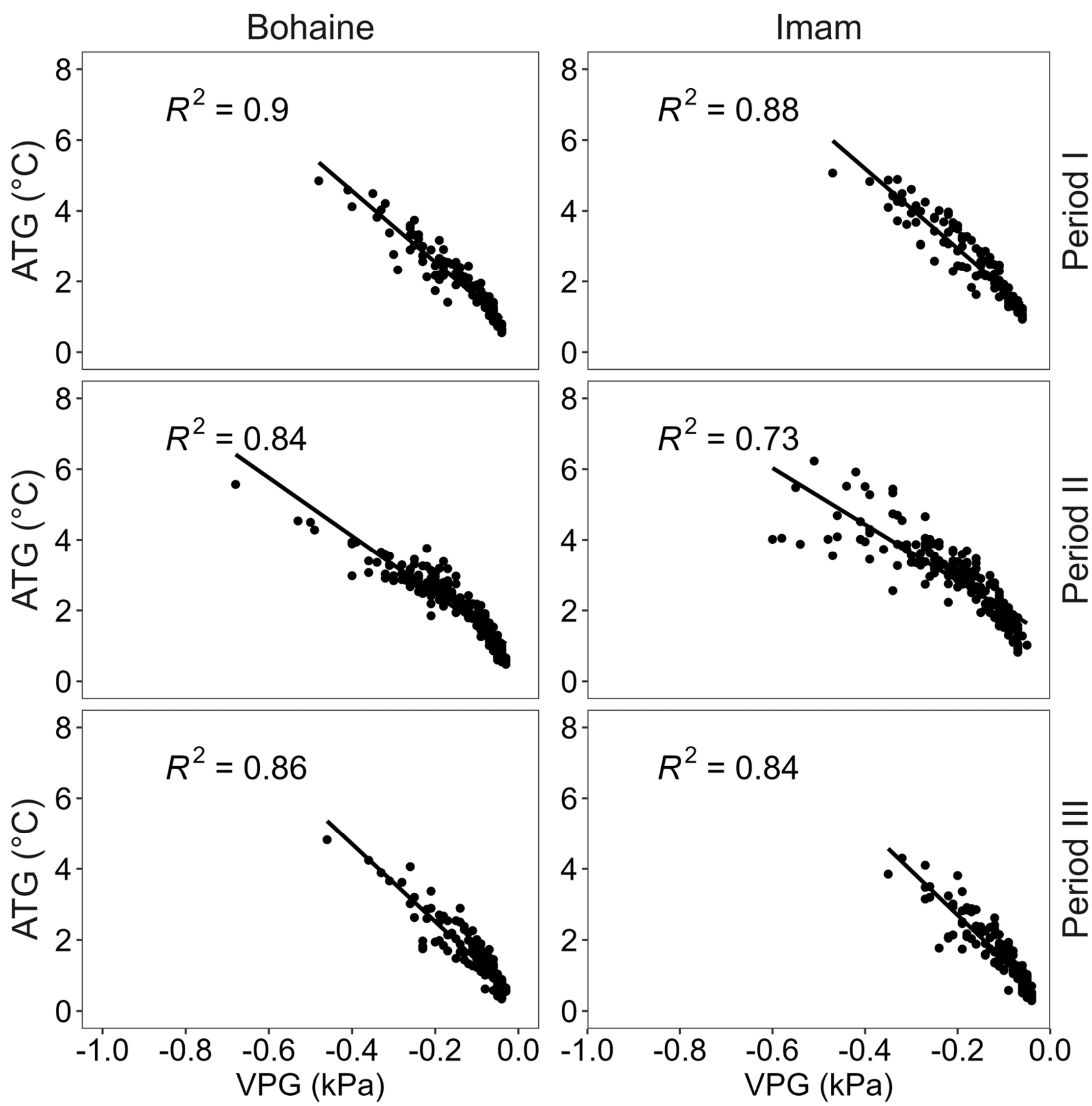

Figure 2.7 Relationships between above-canopy air temperature gradient (ATG) and above-canopy water vapor pressure gradient (VPG) during nighttime (hours 19 to 6 of the 24-h day) in irrigated fields of wheat cultivars Imam and Bohaine in periods I (21−30 January 2021), II (31 Jan-uary − 14 February), and III (15−28 February). $P < 0.001$ for all regression lines.

2.4 Discussion

Canopy temperature is an important trait for breeding wheat with heat stress tolerance. Genotypes have been evaluated mainly in small experimental plots (a few meters); since Ts can be measured over a small area of the canopy surface, a radiometric approach, i.e., CTD, has been used for cultivar comparison (Amani et al., 1996; Balota et al., 2007; Reynolds et al., 1994; Thakur et al., 2022). Our study, which was conducted under very high temperatures up to 37 °C (Figure 2.2), showed that the maximum CTD was 6.5 °C in the Bohaine field and 6.4 °C in the Imam field during the late vegetative stage, 6.5 °C and 7.2 °C during the early reproductive stage, and 4.7 °C and 5.0 °C during the late reproductive stage. These values are comparable to those of previous studies in irrigated and similar environments; for example, CTD values for wheat varietal differences reported from south-central Mexico ranged widely from 5.0 to 7.9 °C during pre-heading, from 4.8 to 9.1 °C during heading/anthesis, and from 4.1 to 7.3 °C during grain filling (Amani et al., 1996). Thus, CTD under irrigated conditions in arid environments is large because dry air promotes transpiration, resulting in more evaporative cooling of the canopy. This indicates that the ambient temperature of the canopy in such microclimates can be modified to be considerably lower than the critical high temperature for the growth and development, e.g., 31.0 °C around anthesis and 35.4 °C during grain-filling (Balota et al., 2008). On the other hand, CTD is negative in some cases: that is, Ts > Ta, owing to water stress in the field (Balota et al., 2007).

Although canopy temperature is rarely measured at night, it can be used to compare cultivars in high-temperature environments. For example, Balota et al., (2008) showed differences in CTD among wheat cultivars during the predawn hours. Similarly, our study showed that Ts at night was lower than Ta, and thus revealed cultivar differences in CTD (Figure 2.5). This lowered canopy surface at night could be due to radiative cooling (Luchiari Jr. et al., 1997) or to cooling by nocturnal transpiration (Rawson & Clarke, 1988) in calm air. This implies that nighttime cooling is favorable for crop growth, since leaf respiration is reduced when temperatures drop (Posch et al., 2021; Toddl, 1982).

There are only a few previous comparisons of Ts and Tc in wheat. Our study showed that Ts < Tc (Figure 2.4). Similarly, previous studies in various climatic zones showed that Ts < aerodynamic surface temperature at high sensible heat flux in temperate central England (Huband & Monteith, 1986a) and arid Phoenix, Arizona, USA (Choudhury et al., 1986). The difference between the two temperatures is due to the fact that Ts, which reflects leaf moisture status, is based on radiative emission from the canopy (Ehrler, Idso, Jackson, & Reginato, 1978; Ehrler, Idso, Jackson, Reginato, et al., 1978; Jackson et al., 1977, 1981; Pinter et al., 1990), whereas Tc is due to the energy balance of the canopy, especially sensible heat loss from the canopy to the boundary layer above the canopy surface (Choudhury et al., 1986; Huband & Monteith, 1986a). In addition, the relationship of aerodynamic surface temperature with Ts can be discriminated by wind speed

(Huband & Monteith, 1986a), but the effect of WS on the ATG–CTD relationship was not clear in our results.

Clarifying the micrometeorological relationship between canopy temperature and atmospheric water vapor may provide a better understanding of the mechanisms that lead to cultivar differences in crop response to high-temperature environments. Wind speed has a significant effect on the loss of sensible heat from the canopy surface and thus on the aerodynamic estimation of canopy surface temperature from the vertical profiles (gradients) of temperature and humidity (Huband & Monteith, 1986a; Monteith, 1981). ATG was negatively correlated with VPG, but the weaker daytime ATG–VPG relationship, at higher WS (Figure 2.6), could be due to the turbulent flux of heat and water vapor. The stronger relationship at nighttime (Figure 2.7), at lower WS, can be interpreted as the retention of cold, moist air below the boundary where warmer, dry air has little flow; that is, the horizontal flux of heat and water vapor over the canopy could be slowly stable.

Our study further showed a cultivar difference in ATG (Figure 2.5), as the canopy of Imam was cooler than that of Bohaine. This difference could be attributed to the large difference in NDVI (as a proxy for LAI and aboveground biomass) between cultivars (Figure 2.2), as in the positive relationship of CTD with LAI and aboveground biomass in a similar environment in northwest Mexico reported by Ayeneh et al., (2002). As the two fields received full irrigation, Imam, which has a higher LAI and a denser canopy and is recommended for dry irrigated environments of Sudan (Tahir et al., 2017), could perform better than Bohaine under non-limiting water conditions in terms of the ability to meet atmospheric evaporative demand during the daytime and rehydrate overnight to recover from diurnal wilt, implying that cultivars with a prostrate dense canopy are better adapted to hot and dry environments than those with an erect canopy. This is supported by the recently reported finding (Chai et al., 2022) that the cultivar difference in CTD can result from their morphological difference. But when we consider the phenological characteristics of these two cultivars, fast-maturing Bohaine with a lower yield potential than long-maturing Imam is still needed when the optimum sowing period for Imam cannot be met.

Based on this study, it has been discovered through micrometeorological observations that wheat displays distinct reactions to high-temperature stress. This indicates that different cultivars possess varying mechanisms of adaptation to heat stress, with those that are more accustomed to high temperatures demonstrating a greater ability to modify the microclimate. In addition, significant information provided in this study can fill the gap in understanding microclimate modification which can be used in enhancing crop yield through various techniques available, such as shading, windbreak, anti-transpirant application, optimized sowing parameters, intercropping, irrigation, and nutrient management (Biswas et al., 2023).

2.5 Conclusions

This study demonstrates the potential of the micrometeorological approach to ex-plain cultivar differences in the response of irrigated wheat to high temperatures. There were large differences in ATG and VPG between cultivars. ATG was negatively correlated with VPG, and the relationship was stronger in the nighttime, when wind speeds were lower. The cultivar difference was clear during both daytime and nighttime in all three critical growth periods, as air temperature and vapor pressure always had larger gradients in the Imam field than in the Bohaine field. In practical application, once genotypes are screened for high-temperature stress tolerance at the small-plot scale through the use of CTD, the micrometeorological approach can be used to verify their performance at the field scale. The information generated in this study is useful for improving wheat crop management techniques for an optimal canopy architecture that can enhance their capacity to alter the microclimate in hot environments.

Chapter 3

3 Characterization of the Energy Balance of Wheat Grown under Irrigation

3.1 Introduction

Climate change is becoming an increasingly pressing issue, and its impact on agriculture has been found in various regions to affect land suitability for cultivation and crop productivity (Foley et al., 2005). The challenge posed by climate change is particularly severe in hot, dry environments, which are prone to water scarcity and heat waves that can harm crops. In fact, high-temperature stress has a far-reaching effect on crop production through a negative effect on vital growth stages (Ferris et al., 1998) that manifests as reduced productivity of major (staple) crops (Hussain et al., 2019; Ray et al., 2015). In particular, the productivity of wheat (Triticum aestivum L.), which is adapted to cool environments, is severely limited by heat stress (Asseng et al., 2015, 2017; Wheeler & von Braun, 2013). In hot, dry environments where temperatures are rising because of climate change, it has become increasingly important to grasp how evaporative cooling might affect wheat grown under irrigation. This effect can act as a shield against heat stress, thereby mitigating adverse impacts on crop reproductive processes (Ghafarian et al., 2022; Thiery et al., 2017). Moreover, this cooling effect can lead to enhanced water use efficiency (Luchiari Jr. et al., 1997), by creating a microclimate with reduced evaporative loss of moisture from the soil and by fostering atmospheric conditions more conducive to evapotranspiration.

Irrigation significantly affects the energy balance at the crop canopy surface such that the air temperature decreases above the canopy (Bonfils & Lobell, 2007; Li et al., 2020; G. Liu & Wang, 2023; Sacks et al., 2009; Thiery et al., 2017; Zhu & Burney, 2022). By providing crops with more water, irrigation increases evapotranspiration, the process by which water is transferred from the land to the atmosphere via transpiration and evaporation, and, thus, the latent heat flux (LE), which absorbs energy from the atmosphere and cools the crop microclimate (Li et al., 2020; G. Liu & Wang, 2023; Thiery et al., 2017). Irrigation can also affect the canopy surface albedo, which is the amount of solar radiation reflected back into the atmosphere (G. Liu & Wang, 2023). A well-watered crop field tends to have a larger leaf area index, which in turn increases the absorption of solar radiation by the crop; this increased absorption results in elevated transpiration and decreases the available energy for warming the air (Hammerle et al., 2008). Irrigation can also influence transfers of heat from the surface to the atmosphere through conduction and convection, that is, the sensible heat flux (H). Previous studies have shown that irrigation reduces H, which lowers the air temperature (G. Liu & Wang, 2023; X. Liu et al., 2019; Thiery et al., 2017).

Several studies have demonstrated that irrigation can significantly affect the local climate by modifying water and energy budgets. In fact, irrigation can cool the area surrounding an irrigated field (Kang & Eltahir, 2019; Kueppers et al., 2007; Ozdogan et al., 2010)., 2010) because increased soil moisture enhances the thermal conductivity and heat capacity of the soil (Bonan, 2015). Tang et al., (2022) studied the effect of sprinkler irrigation on winter wheat and showed that LE was higher during the daytime and lower at night under irrigation compared with under non-irrigated conditions. Consistent seasonal changes observed in evapotranspiration and heat fluxes have been attributed to the expansion of irrigated cropland and, thus, the cooling effect of irrigation (Jiang et al., 2014; Vote et al., 2015). Moreover, Siebert et al., (2017), who conducted a study in Europe, reported that irrigation can reduce heat stress. In addition, when they modeled crop yield without considering this effect, the effect of heat stress on yield was amplified. However, the incorporation of a localized cooling effect in climate–crop modeling remains a major challenge, particularly when upscaling from leaf to plant to canopy to the landscape. The evaporative cooling effect of irrigation depends on several factors, including the crop type, the background climate, and the irrigation method used. The different water requirements and transpiration rates of different crops can affect the cooling effect (G. Liu & Wang, 2023). Moreover, the effectiveness of irrigation in inducing cooling may be influenced by background climate conditions, such as the availability of water and the action of other cooling mechanisms such as ground surface shading (crop density).

The analysis of microclimate is essential for assessing the appropriateness of the atmospheric environment for crops (Gardner et al., 2021) because it facilitates a granular examination of energy partitioning between sensible heat (transferred through the air) and latent heat (resulting from evapotranspiration) over crop fields. These parameters (LE and H) are often quantified by using the Bowen ratio (BR) (Bowen, 1926), which is a foundational metric in micrometeorological analysis. This approach offers a robust framework for comparing cultivars, particularly in high-temperature environments (Mohammed et al., 2023). Moreover, such an examination can reveal how vegetation profoundly influences the local microclimate by actively modulating energy exchanges.

Sudan produces wheat under irrigation in a hot, dry environment that has been classified into CIMMYT's Wheat Breeding Mega-Environment 5 (Rajaram et al., 1993), and the northern part of the country, which is situated in a hot desert climate zone, is particularly arid. Therefore, the main objective of this study was to characterize the energy balance of wheat grown under irrigation in the hot-arid environment of northern Sudan. The specific objectives were to (i) compare air temperature between a wheat field and the surrounding arid expanse, (ii) quantify the components of the energy balance, and (iii) clarify the effect of irrigation on the energy balance. This study is one of the first to investigate the modification of a wheat microclimate by irrigation at the field level in a hot-arid environment.

3.2 Materials and Methods

3.2.1 Field Experiments

The study was conducted during the dry season (November–April) at the Dongola Research Station of the Agricultural Research Corporation (19.1370°N, 30.4595°E) in a major wheat-producing area of northern Sudan (Figure 3.1) where wheat cultivation depends on irrigation due to the absence of rainfall. Field experiments were carried out during two growing seasons: 2021–2022 and 2022–2023. In 2021–2022, the field was 270 m long in the north-south direction and 180 m wide, and in 2022–2023, it was 290 m long and 200 m wide. Before planting land preparation was conducted by harrowing and leveling. For the experiments, the wheat cultivar Imam was used. Imam is a commercial cultivar introduced by CIMMYT (Attila) and become popular in dry environments like Sudan that is, known for its semi-prostrate growth habit and late maturation (Tahir et al., 2017). In the study field, the crop rows were spaced 0.2 m apart in the north–south direction, and the seeding rate was 120 kg ha^{-1}. The date of sowing was 25 November in 2021–2022 and 2 December in 2022–2023. Immediately after the sowing, the field was flood-irrigated at a rate of 40–50 mm per irrigation, and it was subsequently irrigated every 9 to 26 days, for a total of 9 or 10 times each season. The soil of the field is substantially sandy clay loam with a pH of 8.0, its texture is sandy clay loam at a depth of 0–30 cm and silty clay loam at 30–60 cm, and the organic matter deficiency is significant (< 5%); remarkably, the nitrogen and phosphorus contents are low(Elbashir et al., 2017). Thus, Diammonium phosphate fertilizer, 25 kg N ha^{-1} and

28 kg P ha−1, was evenly applied to the field prior to the sowing, and an additional 56 kg N ha−1 of urea split into two parts was applied during the second and fourth irrigations. The same agronomic management was carried out in both seasons as per the recommendations of the Agricultural Research Corporation of Sudan.

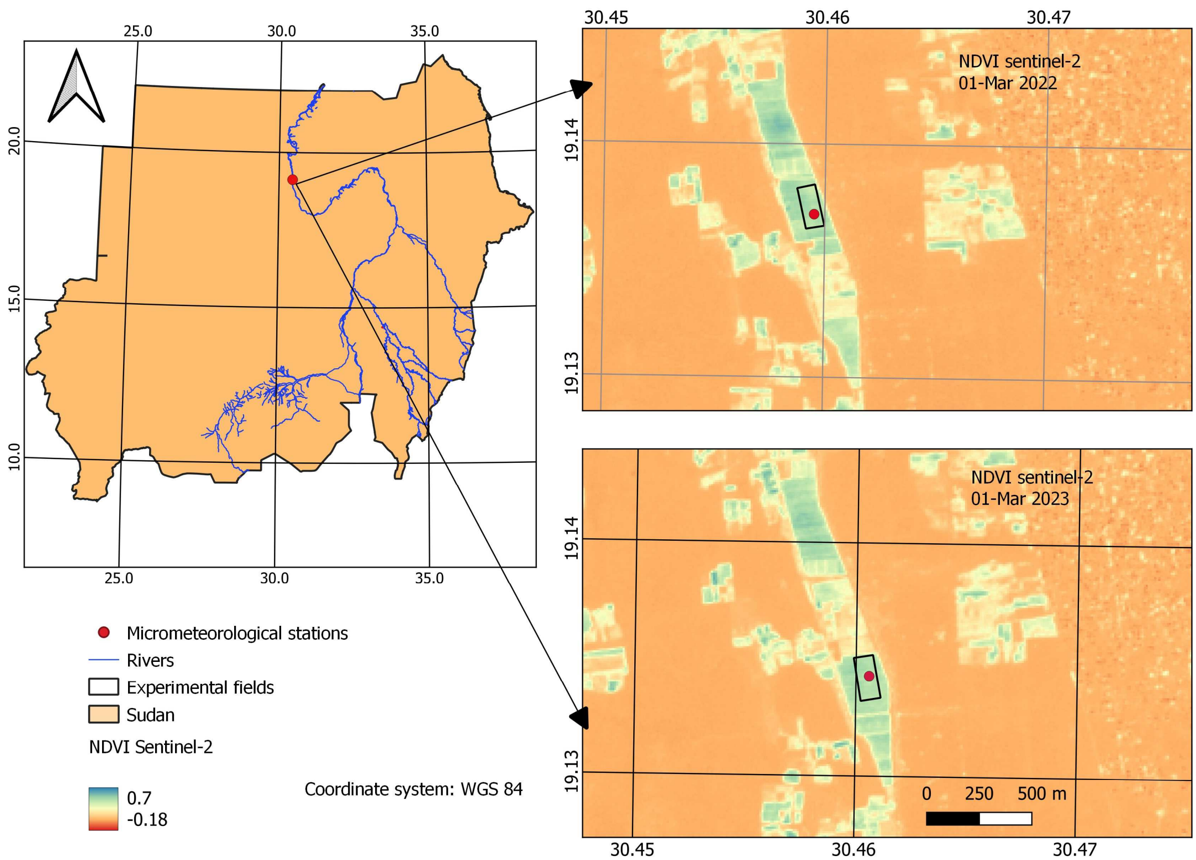

Figure 3.1 The location of the experimental field of wheat grown under irrigation in Dongola, Sudan, shown on Sentinel-2 satellite-based Normalized Difference Vegetation Index (NDVI) maps acquired on 1 March in 2022 and 2023.

3.2.2 Data Collection and Processing

3.2.2.1 Micrometeorological Data

A micrometeorological station was installed in the center of the field with more than 130 m of fetch in the northward direction to measure air temperature (T), relative humidity, net radiation (Rn), soil heat, soil moisture, and wind speed (WS) and direction. The temperature and humidity were measured at a height of 2 m and at the canopy level with HMP155 probes (Vaisala Oyj, Vantaa, Finland) in forced-ventilation shelters. Rn was measured at a height of 2 m with a net radiometer (NR-LITE2, Kipp & Zonen B.V., Delft, The Netherlands). The soil heat flux (G) was measured at a depth of 5 cm with a self-calibrating soil heat flux plate (HFP01SC-L, Hukseflux, Delft, The Netherlands). The depth of the plate was checked periodically after irrigation to ensure that the soil cover above the plate had not been eroded during the flooding. The soil moisture profile was measured at depths of 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5 m with a SoilVUE10 sensor (Campbell Scientific Inc., Logan, Utah, USA). The soil heat flux and soil moisture sensors were installed 0.7 m away from the station. Wind speed and direction were measured with Wind Sentry anemometers and vanes (3002-47A, R.M. Young Co., Traverse, Michigan, U.S.A.), which were installed at a height of 2 m and at canopy level on the windward side of the station. The heights of the sensors for temperature, humidity, wind speed, and direction installed at the canopy level were periodically adjusted to the canopy surface. The data were collected with high temporal resolution: readings were taken every second, then averaged and stored at 10-minute intervals by a datalogger (CR1000X, Campbell Scientific Inc., Logan, Utah, U.S.A.). The micrometeorological measurements were begun on 6 February 2022 and on 17 January 2023 during the first and second growing seasons, respectively, and they ended on 31 March in both seasons.

3.2.2.2 Calculations of Latent and Sensible Heat Fluxes

The Bowen ratio (BR), the ratio of H to LE, was used to calculate both fluxes (in W m−2) over the field as follows:

$$LE = (Rn - G)/(1 + \beta) \quad (1)$$

$$H = \beta(Rn - G)/(1 + \beta) \quad (2)$$

where Rn and G are also expressed in W m−2. BR, which is defined as the ratio of the temperature and water vapor pressure gradients above an evaporative surface, was calculated as follows:

$$BR = H/LE = \gamma(\Delta T/\Delta e) \quad (3)$$

where γ (kPa °C−1) is the psychrometric constant and ΔT (°C) and Δe (kPa) are the vertical differences in the air temperature and atmospheric water vapor pressure, respectively, above the canopy. LE, H, and BR were calculated with the 10-minute interval data and then averaged over the main daytime hours of 8:00 to 16:00 local time (from hours 8 to 15), on one day before and one day after the irrigation. The vapor pressure (e) was calculated from the relative humidity and air temperature (Allen et al., 1998).

3.2.2.3 Meteorological Data

The 2-m temperature data from the micrometeorological station were compared with daily maximum temperature data for the surrounding non-vegetated environment recorded at the Dongola meteorological station (19.167°N, 30.483°E) and obtained from the Sudan Meteorological Authority. Dongola meteorological station is located about 4 km away from the experimental field.

3.2.2.4 NDVI

The Normalized Difference Vegetation Index (NDVI) was used to capture vegetation dynamics (green canopy cover) during the growing season. NDVI is computed as follows:

$$NDVI = (NIR - Red)/(NIR + Red) \quad (4)$$

where NIR and Red are the reflectance values in the near-infrared and red spectral bands, respectively. Google Earth Engine was utilized to process European Space Agency Sentinel-2 satellite imagery with a spatial resolution of 10 m × 10 m (https://sentinels.copernicus.eu/web/sentinel/home). Grid data averaged over areas of 200 m × 90 m (2021–2022) and 210 m × 95 m (2022–2023) in the central part of the experimental field were used as representative NDVI values.

3.2.3 Statistical Analysis

Crop growth was analyzed in terms of NDVI during the first half (1st to 15th day) and second half (16th day to the end) of each study month. Then, NDVI from December to April was compared between the two growing seasons by an unpaired t-test. The daytime irrigation cooling effect during the observation period was evaluated by comparing daily maximum temperatures between the micrometeorological station and the nearby meteorological station by a paired t-test. The significance level for the t-tests was set at 0.05. The effect of irrigation on each component (Rn, LE, H, and G) of the energy balance was assessed by linear regression analysis; that is, the value of each component on the days after irrigation (y) was regressed against that on the days before irrigation (x). In this study, the regression line forced through the origin (with no intercept) was applied to estimate the slope (β), as follows (Kozak & Kozak, 1995):

$$\beta = \sum_{i=1}^{n} x_i y_i / \sum_{i=1}^{n} x_i^2 \quad (5)$$

where n is the number of data points. When β was higher than unity (i.e., β > 1), the flux was determined to have increased after irrigation, whereas β < 1 meant that it had decreased. The coefficient of determination for the no-intercept regression (R2) was calculated using the residual sum of squares and the corrected total sum of squares as follows (Kozak & Kozak, 1995):

$$R^2 = 1 - \sum_{i=1}^{n}(y_i - \widehat{y_i})^2 / \sum_{i=1}^{n}(y_i - \bar{y})^2 \quad (6)$$

where ŷ comprises the estimated values from the no-intercept regression equation (= βx), and ȳ is the mean of the observed values. All statistical analyses were performed with R software (R Core Team, 2023).

3.3 Results

3.3.1 Crop Growth

Crop growth was estimated from the seasonal change of NDVI (Figure 3.2). In the initial stage (December) of the 2021–2022 season, NDVI was low (around 0.05) in the first half of the month and increased immediately after sowing, up to 0.13 at the end of the second half. As the wheat field approached full canopy development in January, the late vegetative growth phase, its vegetative cover became more vigorous; NDVI ranged from 0.27 to 0.36 in the first half of the month and increased sharply to 0.45 in the second half. In February, the early reproductive growth phase, the wheat field reached the heading and flowering stages, and NDVI was stagnant, ranging between 0.27 and 0.30 in the first half of the month and between 0.25 and 0.30 in the second half. In March, the beginning of the maturity stage, NDVI decreased from 0.30 in the first half of the month to 0.11 in the second half, as the critical grain-filling stage was entered. In April, mean NDVI values during the first half (0.09) and the second half of the month (0.08) reflected a trend toward senescence. This discernible decline observed across the wheat field resulted from a reduced green canopy and marked the end of the growing season.

Similarly, in the 2022–2023 season, mean NDVI values in December (0.04 in the first half and 0.12 in the second half of the month) (Figure 3.2) were low because the wheat crop was not yet sown or still in the early vegetative phase. The NDVI started to increase in January; mean values were 0.29 in the first half and 0.36 in the second half of the month, when the crop reached full canopy cover and the end of vegetative growth. The NDVI did not differ in December and January between the two seasons ($p > 0.05$). In February, the NDVI started to gently decrease from the peak, and then it sharply decreased from 0.31 in the first half of March to 0.18 in the second half as the crop reached the maturity stage. In April, a further decrease in NDVI was observed; mean values were 0.12 in the first half of the month and 0.09 in the second half. In both the first and second half of February and the first half of March, the NDVI was significantly higher in 2022–2023 than in 2021–2022 ($p \leq 0.05$). A difference between the seasons was also observed in the first half of April ($p \leq 0.05$).

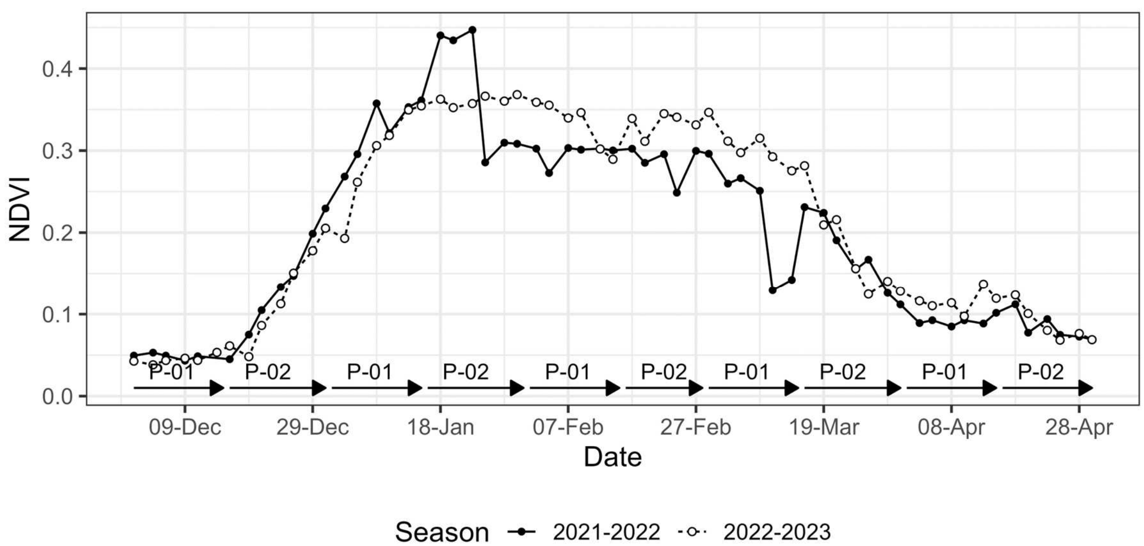

Figure 3.2 Seasonal changes in Sentinel-2 satellite-based NDVI values of the irrigated wheat field in Dongola, Sudan, in the 2021–2022 and 2022–2023 growing seasons.

3.3.2 Evaporative Cooling Effect

The wheat field exhibited a noteworthy cooling trend during each growing season. In the 2021–2022 season, daily maximum temperatures observed at a height of 2 m were lower at the micrometeorological station than at the nearby Dongola meteorological station (Table 1, Figure 3.3); this difference indicated a modification of the microclimate in the wheat field. In the first half of February, the mean temperature showed a significant cooling effect of 2.5 °C on average ($p \leq 0.05$). In both the first and second half of March, the wheat field experienced further cooling ($p \leq 0.05$); during these periods, the mean temperature in the field was 5.3 °C and 2.5 °C, respectively, lower than in the surrounding area.

In the 2022–2023 season, temperatures were also lower in the wheat field than in the surrounding area (Table 1, Figure 3.3). The wheat field showed a significant cooling effect of 5.7 °C and 3.5 °C in the first half of February and in March, respectively ($p \leq 0.05$). However, no significant cooling effect was observed in either the second half of January or in February or March ($p > 0.05$).

Table 0.1 Summary of daily maximum, minimum, and mean temperatures at the micrometeorological station (2-m level) of the irrigated wheat field and its nearby meteorological station in Dongola, Sudan. SD denotes standard deviation.

Season	**Month**	**Period of month**	**Micrometeorological station in the wheat field (°C)**				**Dongola Meteorological station (°C)**				**Temperature difference (°C)**		
			Max	Min	Mean	SD	Max	Min	Mean	SD	Max	Min	Mean
2021–2022	February	Second	28.5	21.7	25.4	1.9	31.8	24.4	27.9	1.9	3.3	2.7	2.5
	March	First	34.8	22.5	29.8	4.4	36.8	30.5	35.1	1.7	2.0	8.0	5.3
	March	Second	39.2	23.7	30.0	4.0	36.5	28.6	32.5	2.3	−2.7	4.9	2.5
2022–2023	January	Second	32.7	24.0	27.8	2.2	28.3	21.1	25.1	2.5	−4.4	−2.9	−2.7
	February	First	30.0	20.9	24.9	2.7	32.1	29.6	30.6	0.7	2.1	8.7	5.7
	February	Second	30.7	22.1	27.3	2.5	30.6	23.4	28.0	2.5	−0.1	1.3	0.7
	March	First	35.6	27.5	31.9	2.4	36.9	34.4	35.4	0.7	1.3	6.9	3.5
	March	Second	36.2	28.6	31.8	2.3	35.4	28.2	32.3	2.5	−0.8	0.4	0.5

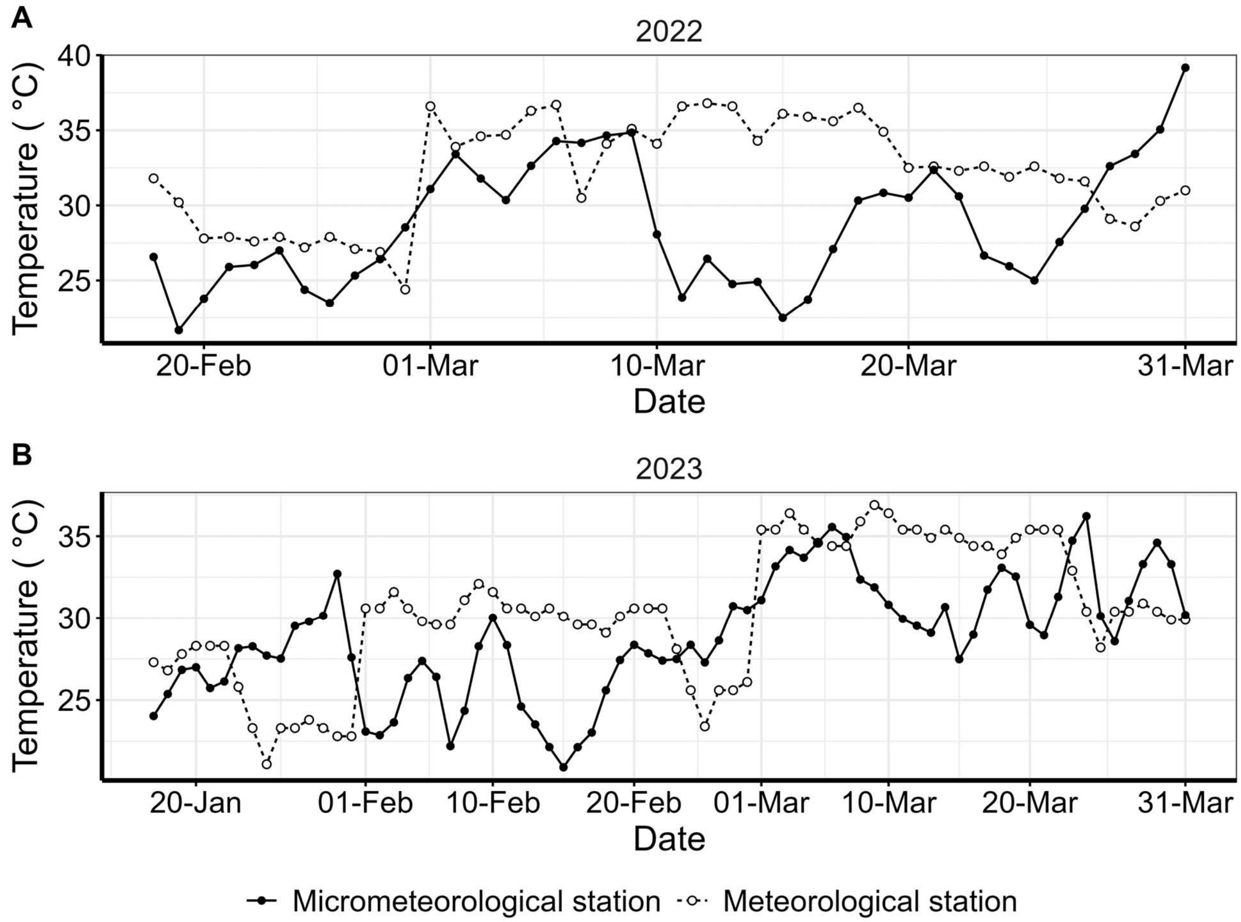

Figure 3.3 Seasonal changes in daily maximum temperature between the micrometeorological station (2 m height) in the irrigated wheat field and the nearby Dongola meteorological station in the (A) 2021–2022 and (B) 2022–2023 seasons.

3.3.3 Seasonal Changes in Micrometeorological Parameters

Figure 3.4 shows the seasonal changes in the 10-minute air temperature (T), water vapor pressure (e), net radiation (Rn), soil heat flux (G), and wind speed (WS). T at canopy level was generally lower than at a height of 2 m during the daytime (hours 8–15) throughout the measurement periods. In both seasons, a large (4 °C) difference between the two heights was observed in March; the maximum 2-m temperature during March reached 39.4 °C in the 2021–2022 season and 36.6 °C in the 2022–2023 season. In contrast, vapor pressure (e) was higher at canopy level than at a height of 2 m. WS at a height of 2 m was high during the daytime, averaging 3.4 m s−1 in both seasons, and the maximum WS was observed in February. The wind direction was generally northerly (in all cases between northeast and northwest). In both seasons, Rn increased sharply in the morning, peaked around midday (to a maximum of 749 W m−2 in 2021–2022 and 767 W m−2 in 2022–

2023), and then decreased in the afternoon. G was negative in early morning and late afternoon, and its peak was observed around the mid-day (maximum of 83 W m−2 in 2021–2022 and 155 W m−2 in 2022–2023).

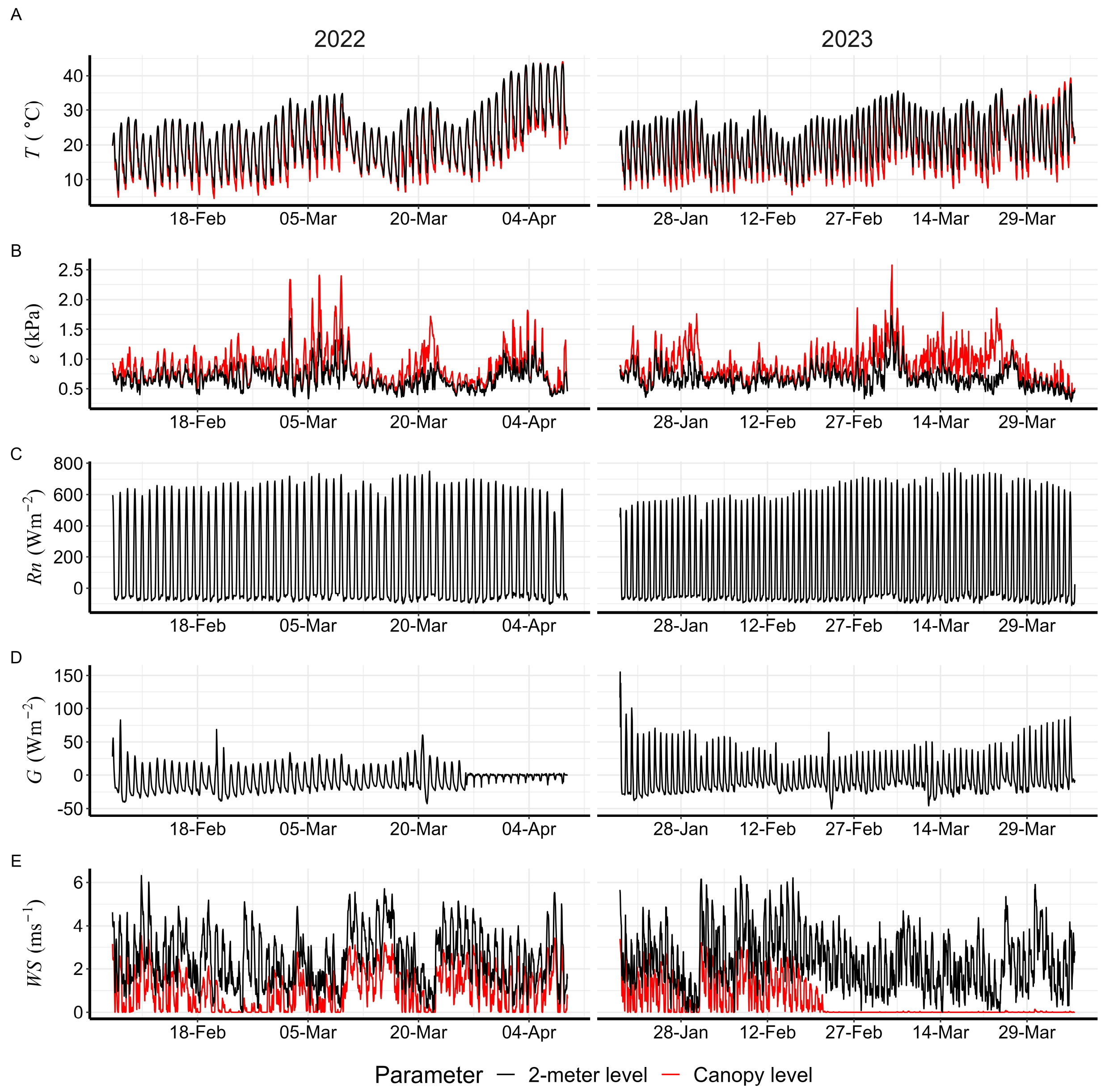

Figure 3.4 Seasonal changes in (A) air temperature (T), (B) water vapor pressure (e), (C) net radiation (Rn), (D) soil heat flux (G), and (E) wind speed (WS) in the irrigated wheat field in Dongola, Sudan, in the 2021–2022 and 2022–2023 seasons. The temperature, vapor pressure, and wind speed were measured at both a height of 2 m and at canopy level.

3.3.4 Energy balance

The Bowen ratio (BR) was mostly negative throughout the growing season (92.2% and 93.1% of the time in 2021–2022 and 2022–2023, respectively); it was lower in early morning and in late afternoon than around midday, and it tended to decrease after irrigation (Figure 3.5). The soil moisture content was constant during the days before and after irrigation, but it was higher after irrigation than before irrigation. In both seasons, LE was higher than Rn during most daytime hours, particularly when the crop canopy was fully developed in late February to early March (Figure 3.5). The difference between LE and Rn was larger on the days after irrigation than on the days before irrigation. Because of the negative BR, H was also negative and large; thus, energy was transferred from the atmosphere to the canopy, particularly in the afternoon. In contrast, H tended to be low early and late in the season (late January, early February, and late March). With regard to the partition of energy for evapotranspiration, in the 2021–2022 season, the radiation-driven [= (Rn – G)/LE] and air-driven (= –H/LE) parts of LE decreased from 0.95 to 0.85 and increased from −0.05 to −0.14, respectively, after irrigation (averaged over hours 10–13 on the four days). In the 2022–2023 season, (Rn – G)/LE decreased slightly from 0.88 to 0.86, but –H/LE increased considerably from −0.08 to −0.33.

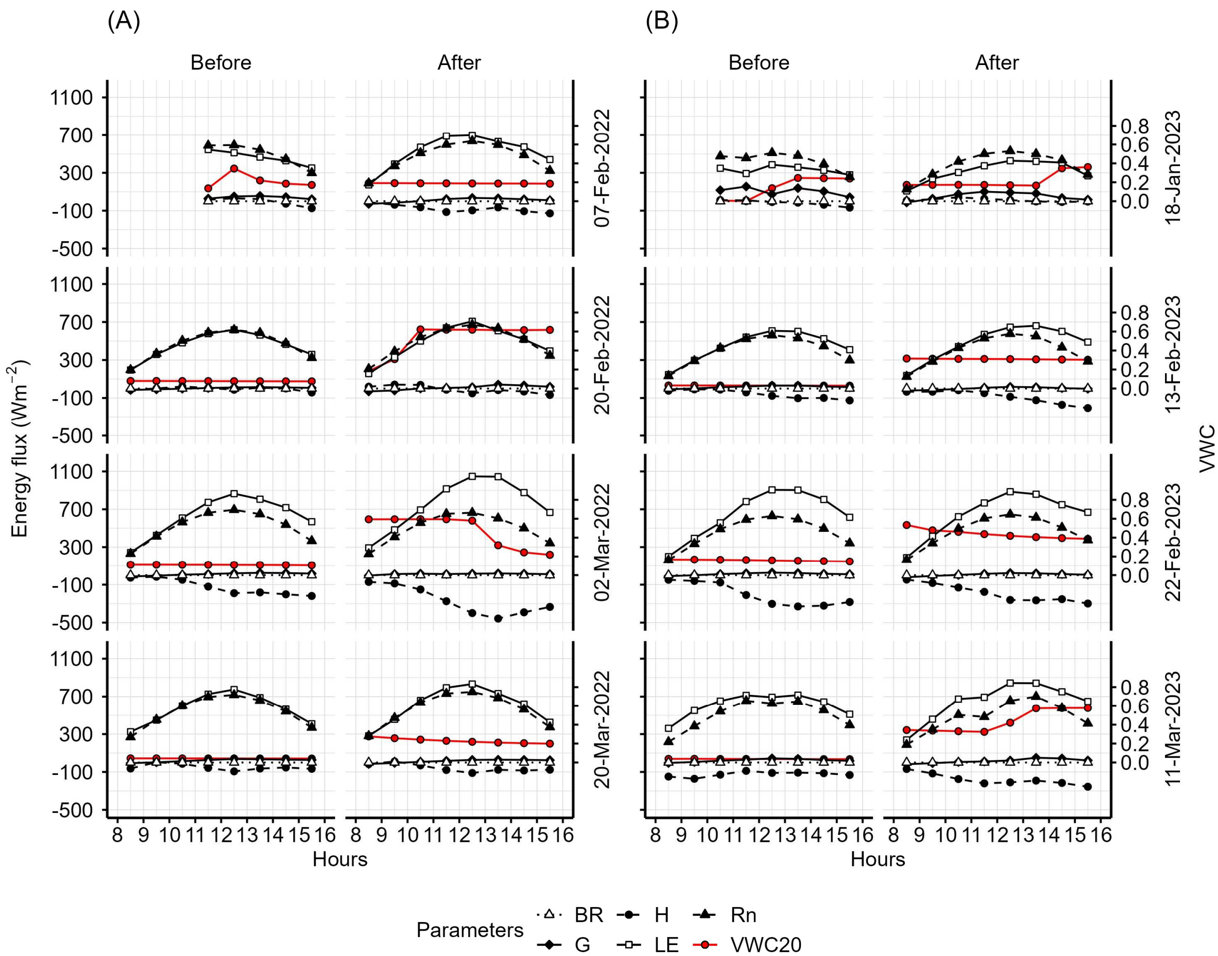

Figure 3.5 Daytime (hours 8 to 15) changes in the Bowen ratio (BR), energy balance components [net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G)], and soil moisture content averaged over depths of 0.1 m to 0.2 m (VWC20) on the days before and after irrigation in the wheat field in Dongola, Sudan, in the (A) 2021–2022 and (B) 2022–2023 growing seasons. The irrigation dates are shown to the right of the panels.

Figure 3.6 shows the relationships of the energy balance components averaged over hours 8–15 between the days before and after the dates of irrigation. Strong positive relationships were observed for Rn (R2 = 0.78), LE (R2 = 0.92), H (R2 = 0.70), and G (R2 = 0.89) between the days before and after irrigation. Rn showed no change after irrigation; the regression line had a slope (β) of 1 and lay on the 1:1 line. LE increased after irrigation; the regression line had a slope greater than 1 and plotted above the 1:1 line. H also increased after irrigation because the regression line had a slope greater than 1. G decreased after irrigation because the slope of the regression line was much less than 1.

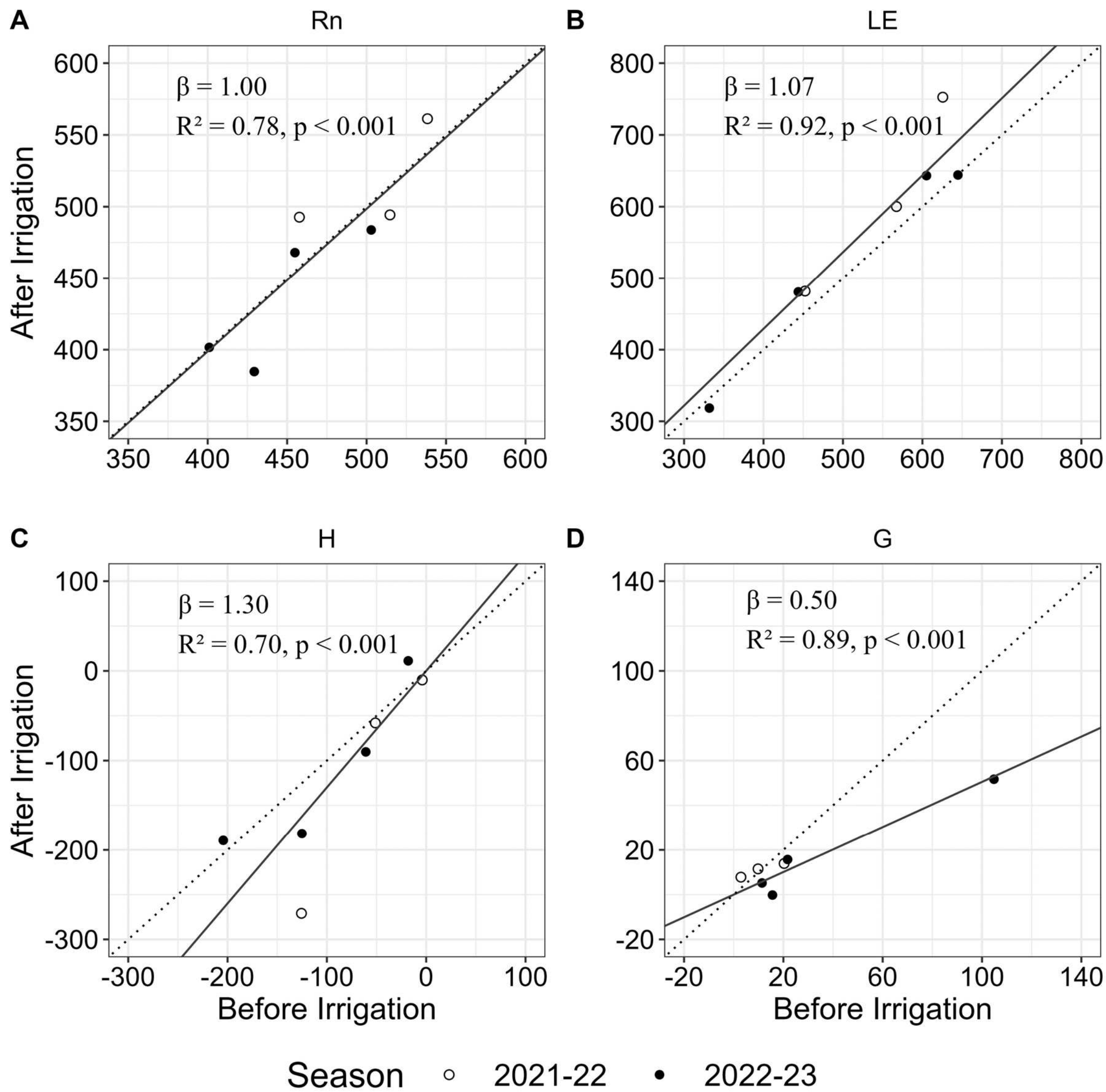

Figure 3.6 Relationships between the energy balance components averaged over hours 8–15 on the days before and after irrigation in the wheat field in Dongola, Sudan: (A) net radiation (Rn), (B) latent heat (LE), (C) sensible heat (H) and (D) soil heat (G). The linear regression analyses used the combined data of the 2021–2022 and 2022–2023 seasons, but the irrigation on 7 February 2022 was excluded because no data were available for hours 8–10 before irrigation.

3.4 Discussion

Seasonal changes of NDVI reflect the dynamic nature of crop growth and development. As shown in this study, particularly in February and the first half of March (Figure 3.2), the variations of NDVI indicate a strong relationship between crop growth stages and environmental factors such as heat stress, drought stress, and biotic stress (Babar et al., 2006; Cabrera-Bosquet et al., 2011; Hazratkulova et al., 2012; Marti et al., 2007; Raun et al., 2001). Our study found differences in

NDVI between two growing seasons that might be attributable to variations in the growth environment. In both seasons, however, the typical change of NDVI consistently depicted a healthy canopy because the field was fully irrigated. This finding aligns with those of previous studies that highlight the positive effect of irrigation on crop health and productivity (Kueppers et al., 2007; Thiery et al., 2017; Zaveri & B. Lobell, 2019). Variations of the energy balance components during the growing season (Figure 3.5) can be attributed to a seasonal change in the canopy size (i.e., NDVI), because an increased leaf area has been reported to alter energy fluxes above a canopy (Hammerle et al., 2008).

A localized cooling effect generated by well-watered cropland was observed in the study area (Dongola, Sudan), with variations in the magnitude of the cooling across different growth stages (Table 1, Figure 3.3). The most pronounced cooling effect observed was a difference of over 5 °C from the late vegetative to the early reproductive stages; as a result, the wheat was grown under relatively cooler conditions than the surrounding environment. Many previous studies have reported a similar cooling effect (Jiang et al., 2014; Kang & Eltahir, 2019; Kueppers et al., 2007; Ozdogan et al., 2010), but our study is one of the first to report micrometeorological observations that demonstrate irrigation cooling in a hot desert region where sensible heat advection occurs. The shield against heat stress provided by a cooling microclimate is critical for preserving crop reproductive processes (H.-J. Liu & Kang, 2006). In addition, microclimate modification is associated with enhanced water use efficiency because it reduces the evaporative loss of moisture from the soil and fosters atmospheric conditions more conducive to evapotranspiration (Cavero et al., 2009). These findings underline the vital role of irrigation in mitigating the adverse impact of heat stress and improving overall crop health in arid regions. In deserts, this microclimate cooling is known as the oasis effect, which is attributed to a combination of factors, including increased evapotranspiration, shading from dense vegetation, and the presence of water bodies (Flerchinger & Pierson, 1991; Hagishima et al., 2007; Kai et al., 1997; Kotzen, 2003; Manteghi et al., 2015; Potchter et al., 2008; Robitu et al., 2006; Taha et al., 1991; Xiong et al., 2016).

The comparison between the energy balance components, particularly the latent heat flux (LE) and sensible heat flux (H), between days before and after irrigation (Figure 3.5Figure 3.6) provides valuable insights into crop performance. The hot, dry conditions before irrigation caused a significant portion of energy to be allocated to evapotranspiration (i.e., LE), and this energy allocation was efficient for transpiration and therefore crop growth. However, the decrease in the negative Bowen ratio (BR) after irrigation indicates an increased allocation of H to evapotranspiration. This energy reallocation emphasizes the importance of irrigation in maintaining optimal crop conditions in hot-arid environments. In addition, the relative stability of BR throughout the growing season shown in this study indicates an absence of soil moisture stress (Yuan et al., 2017). It also indicates that LE exceeds net radiation (Rn) because of sensible heat advection from the surrounding environment (Luchiari Jr. et al., 1997; Tolk et al., 2006). The increase of Rn after irrigation on 20 February 2022, 20 March 2022, and 22 February 2023 (Figure 3.5) might be attributable to changes in albedo or increases in water vapor caused by the increased soil moisture (Eltahir, 1998).

Another critical facet of this study involves the soil heat flux (G) and its relationship with the soil environment. Our study demonstrated that G was lower during the main growth period (from the late vegetative to the early reproductive stages) and higher during the initial (early vegetative) and maturity (late reproductive) stages (Figure 3.5). A similar result has been reported in a hot environment in India, in the humid subtropical climate zone (Mukherjee et al., 2012). Also, the distinct change of G observed following each irrigation event (Figure 3.6) is primarily attributable to alterations in soil moisture content and, therefore, the thermal properties of the soil (Guan et al., 2009). This dynamic interaction reflects the role of soil as a mediating factor in the energy balance of a flood-irrigated wheat field. Interestingly, the response of wheat to high soil temperature is different between cultivars (Tahir et al., 2005), indicating that the thermal environment of the soil is important for cultivar improvement in hot-arid regions.

3.5 Conclusions

The energy balance of wheat grown under irrigation in the hot-arid environment of Sudan was investigated during two growing seasons. An evaporative cooling effect was observed as a significant difference in air temperature between the field and the surrounding desert area. This difference increased after the crop reached full canopy cover, because LE was the dominant component of the energy balance over the other components, H and G. This dominance of LE stabilized BR during the daytime; thus, growing conditions were favorable and abiotic stress due to a soil moisture deficit did not occur. Furthermore, the negative BR due to sensible heat advection during the growing period in the study area meant that H was negative and, hence, LE was larger than Rn. Our study thus provides insight into the use of micrometeorological analysis to quantify the response of irrigated wheat to a hot-arid environment. As global temperatures continue to rise as a result of climate change, the irrigation cooling effect will become more crucial in wheat-producing areas in hot, dry environments. The findings of this study will therefore be useful for understanding soil–plant–atmosphere interactions in such environments.

Chapter 4

General Conclusion

4.1 Conclusion

Sudan produces wheat under irrigation in a hot, dry environment that has been classified into CIMMYT's Wheat Breeding Mega-Environment 5 (Rajaram et al., 1993). However, there is a lack of information on microclimates of irrigated wheat in hot environments to explain crop responses to high temperatures. The analysis of microclimate is essential for assessing the appropriateness of the atmospheric environment for crops (Gardner et al., 2021). Moreover, such knowledge can reveal how vegetation profoundly influences the local microclimate by actively modulating energy exchanges. Therefore, this thesis has been structured to address these gaps by understanding cultivar-specific micrometeorological response (Chapter 2) and also reflected the irrigation-induced modification of wheat microclimate (Chapter 3).

The study aimed to evaluate the performance of two wheat cultivars under irrigated conditions in a hot environment. Specifically, the focus is on understanding the canopy temperature depression (CTD) and the factors that influence it. In Chapter 2, significant differences in CTD between the two wheat cultivars we examined. Imam had a much higher temperature depression than Bohaine, which suggests that it has a better cooling ability and may be less vulnerable to heat stress. This observation makes Imam a promising option for cultivation in Sudan's hot and arid climate. This cooling effect has been observed not only during the daytime, but it has been extended to nighttime during all critical growth periods (vegetative, heading, and grain-filling). The study also revealed that air temperature gradient (ATG) and vapor pressure gradient (VPG) are negatively correlated, and this correlation was greater during the nighttime due to the low wind speed. And this emphasizes that wind speed has a crucial impact in altering the microclimate surrounding the wheat canopy due to the turbulent flux of heat and water vapor. The study revealed that there is a difference in ATG between the two cultivars, Imam and Bohaine. The canopy of Imam was found to be cooler than that of Bohaine, which could be attributed to the significant difference in NDVI between cultivars. NDVI is used as a proxy for LAI (Leaf Area Index) and aboveground biomass.

Clarifying the micrometeorological relationship between canopy temperature and atmospheric water vapor may provide a better understanding of the mechanisms that lead to cultivar differences in crop response to high-temperature environments. This indicates that different cultivars possess varying mechanisms of adaptation to heat stress, with those that are more accustomed to high temperatures demonstrating a greater ability to modify the microclimate. In addition, significant information provided in this study can fill the gap in understanding microclimate modification which can be used in enhancing crop yield through various techniques available, such as shading, windbreak, anti-transpirant application, optimized sowing parameters, intercropping, irrigation, and nutrient management.

The findings mentioned above led to an investigation of the energy balance of Imam in the hot-arid environment of northern Sudan (Dongola) over two seasons (2021-2022 and 2022-2023). The study discovered that irrigation has a significant impact on the microclimate. The wheat canopy showed a localized cooling effect generated by well-watered cropland, with varying degrees of cooling observed across different growth stages. The most significant cooling effect observed was a temperature difference of over 5 °C between the field and the surrounding area, particularly during the late vegetative to the early reproductive stages. This difference increased after the crop reached full canopy cover, because latent heat flux (LE) was the dominant component of the energy balance over the other components, sensible heat flux (H) and soil heat flux (G). As a result, wheat was grown in a relatively cooler environment than the surrounding areas. The preservation of crop reproductive processes relies on the cooling of microclimate to shield against heat stress. These findings highlight the crucial role of irrigation in mitigating the adverse effects of heat stress and improving crop health in arid regions.

The findings of the study suggest that LE is higher than net radiation (Rn) due to the sensible heat advection from the surrounding environment. Another crucial aspect of our study is the relationship between G and the soil environment. The study demonstrated that G was lower during the main growth period (from the late vegetative to the early reproductive stages) and higher during the initial (early vegetative) and maturity (late reproductive) stages.

The study's findings will aid in understanding interactions between soil, plants, and the atmosphere in these environments and can be summarized in the following points: (1) Cultivar-specific response to hot environmental conditions can be identified using micrometeorological information; (2) microclimate modifications due to evaporative cooling effect can be higher even in hot-arid conditions of wheat cultivation in Sudan. The findings of this study will therefore be useful for understanding soil–plant–atmosphere interactions in such hot environments.

4.2 Implications of the thesis and future research

This thesis holds multifaceted implications, fostering advancements in agrometeorology, crop growth modeling, and breeding practices. The study refines our understanding of micrometeorological factors influencing wheat cultivation, particularly in hot\arid environments. Insights into wind-canopy interactions and cultivar-specific responses provide a foundation for agrometeorologists to develop more precise models capturing the complex dynamics within crop canopies.

Incorporating cultivar-specific micrometeorological responses into crop growth models can significantly enhance their accuracy and predictive capabilities. This advancement enables researchers and agricultural practitioners to make more reliable forecasts of crop development, growth, and yield under diverse environmental conditions. By tailoring crop models to specific cultivars, they can better capture the unique physiological and morphological traits that influence plant-micrometeorological interactions.

The identification of cultivar-specific traits associated with favorable micrometeorological responses provides crucial information for breeding programs. Breeders can now target specific genetic markers linked to these traits, contributing to the development of wheat varieties that are more resilient to varying climatic challenges. For instance, breeding for cultivars with enhanced canopy architecture, stomatal conductance, and root systems can optimize micrometeorological conditions around the plant, leading to improved water use efficiency, photosynthetic rates, and overall productivity.

Collectively, these implications underscore the interdisciplinary nature of the study, offering a holistic framework for the advancement of sustainable and climate-resilient agricultural practices. The integration of micrometeorological insights, climate modeling, and breeding strategies provides a comprehensive approach to addressing the challenges posed by evolving environmental conditions.

Future research can leverage remote sensing data and crop growth modeling to advance our knowledge of micrometeorology and energy dynamics in wheat cultivation. Satellite and drone imagery can enhance micrometeorological measurements, while real-time monitoring systems can optimize irrigation practices. Coupling remote sensing data with crop growth models can provide a dynamic and predictive framework for understanding the relationships between micrometeorology, irrigation, and crop development. Incorporating climate change scenarios can offer insights into how environmental changes may interact with micrometeorological factors. Interdisciplinary collaborations between experts in remote sensing, crop modeling, and micrometeorology will be crucial in bridging the gaps between data collection, analysis, and practical applications.

Summary

The impact of climate change on agriculture is critical and demands urgent attention. In Sudan, the agricultural sector is highly vulnerable to climate change, posing threats to food security and national economy. The consequences of climate change, specifically rising temperature, could significantly impact agricultural production in Sudan, affecting crop yields, water availability, and land use. Wheat is one of the major crops in Sudan and is strongly affected by climate change. Sudan produces wheat under irrigation in a hot and dry environment that has been considered one of the hottest wheat-producing areas in the world. Due to its adaptation to cooler environments, wheat is highly susceptible to high temperatures, leading to substantial anticipated effects on yields and the potential for significant reductions in production under future climate. To understand the response of wheat to heat stress, a comprehensive exploration of micrometeorological factors influencing canopy temperature is essential. However, existing knowledge about wheat microclimates in hot and dry environments remains limited. To bridge this gap, the purpose of this thesis was therefore to advance our understanding of microclimates in irrigated wheat cultivation in Sudan. The main objectives were to investigate cultivar differences in the canopy temperature and to characterize the energy balance in the hot-arid environment.

First, the response of two high-yield, heat-tolerant wheat cultivars, Imam and Bohaine, to a hot and dry environment was evaluated. Micrometeorological observations were carried out in two adjacent fields under irrigated conditions in the Gezira Scheme, Sudan. The hourly micrometeorological data were collected at 2-meter and canopy levels in the 2020-2021 growing season to specifically investigate canopy temperature depression (CTD) and its influencing factors. The micrometeorological observations revealed that there was a notable difference between canopy surface temperature and canopy-level air temperature. The former consistently displayed lower owing to the evaporative cooling effect, while the latter factored in both convective and radiant heat exchange reflecting the distinctive thermal exchanges above the canopy. Also, the micrometeorological observations reflected significant differences in CTD between the two wheat cultivars. Imam with a semi-prostrate growth habit had a much higher CTD than Bohaine with a fully erect growth habit, indicating that it has a better cooling ability and can be less vulnerable to heat stress. This cooling effect was observed not only during the daytime but was extended to the

nighttime during all critical growth periods (vegetative, heading, and grain-filling). Besides, the study revealed that air temperature gradient and vapor pressure gradient were negatively correlated, and this correlation was greater during the nighttime due to the low wind speed. This indicates that wind speed has a crucial impact in altering the microclimate surrounding the wheat canopy due to the turbulent flux of heat and water vapor. Furthermore, the difference in canopy temperature between the two cultivars could be attributed to the significant difference in NDVI, which is used as a proxy for the leaf area index and aboveground biomass. This indicates that different cultivars possess varying mechanisms of adaptation to high temperatures, demonstrating a greater ability to modify the microclimate.

Next, the response of irrigated wheat to a hot-arid environment and the effect of irrigation on the microclimate were clarified. Net radiation (Rn), soil heat flux (G), soil moisture, and temperature and humidity at 2-meter height and canopy level were measured in a wheat field in Dongola, northern Sudan in two crop growing seasons (2021-2022 and 2022-2023). The Bowen ratio method was used to calculate the latent heat flux (LE) and sensible heat flux (H). The study discovered that irrigation has a significant impact on the microclimate, as air temperature in the field was lower than that at a nearby meteorological station. The wheat canopy showed a localized cooling effect generated by well-irrigated cropland, with varying degrees of cooling observed across different growth stages. The most significant cooling effect observed was a difference of over 5 °C during the late vegetative to early reproductive stages. This difference increased after the crop reached full canopy cover because LE was the dominant component of the energy balance over H and G. These findings highlight the crucial role of irrigation in mitigating the adverse effects of heat stress and improving crop performance in arid regions. The significant information provided in this study can fill the gap in understanding microclimate modification which can be used in the adaptation measures for enhancing wheat crop yield. In addition, the relationship between G and soil conditions was examined. The study revealed that G had a lower intensity during the main growth period from the late vegetative to early reproductive stages. However, during the early vegetative and late reproductive stages, G was higher. These findings not only contribute to a better understanding of the energy partitioning in the soil-plant-atmosphere continuum but also underscore the seasonal variations in soil heat flux.

This thesis presents insights that enhance our understanding of microclimate and energy balance in wheat cultivation, specifically in hot-arid environments. Firstly, using a micrometeorological approach, the study uncovered substantial differences in canopy temperature between two wheat cultivars, underscoring the importance of incorporating growth habits in such data analyses. Secondly, the study delved into irrigated wheat in a hot-arid environment and identified unique temperature modifications, particularly during the critical growth stages. Thirdly, the study highlighted the potential of the well-watered wheat canopy to produce localized cooling effects, which varied across different growth stages. Furthermore, the study identified the significant role of sensible heat advection in the energy balance, revealing the intricate relationships between the latent heat flux, net radiation, and surrounding environmental conditions. These findings not only deepen our understanding of crop-micrometeorological interactions in wheat cultivation but also offer valuable insights for developing climate-resilient agricultural practices that are tailored to hot-arid environments.

In conclusion, the implications of this thesis can be summarized as: the integration of cultivar-specific micrometeorological responses into crop models has a transformative impact. This inclusion enhances the accuracy of the models and makes more reliable simulations for crop development, growth, and yield under diverse environmental conditions. Tailoring the micrometeorological approach to specific cultivars increases precision by capturing unique morphological traits pivotal in crop-micrometeorological interactions. Furthermore, identifying cultivar-specific traits that harmonize with given microclimates provides critical insights into plant breeding, as breeding strategies that focus on traits such as canopy architecture and leaf area size align with optimizing micrometeorological conditions. This knowledge enables the targeted selection of traits associated with resilience to varying climatic challenges, paving the way for the development of wheat cultivars that can withstand diverse environmental conditions. Therefore, the application of micrometeorological insights in both crop modeling and plant breeding signifies a significant stride toward advancing climate-resilient and productive agricultural practices in the hot-arid environment of Sudan.

要旨

気候変動が農業に及ぼす影響は深刻であり、早急な対策が必要である。スーダンの農業セクターは気候変動に対して非常に脆弱であり、食糧安全保障と国民経済に対する脅威となっている。気候変動の影響、特に気温の上昇は、スーダンの作物収量、水の利用可能性、土地利用を含む農業生産に大きな影響を与える可能性がある。コムギはスーダンの主要作物のひとつであり、気候変動の影響を強く受ける。スーダンは世界で最も暑いコムギ生産地のひとつであり、高温で乾燥した環境で灌漑によりコムギを生産している。コムギは冷涼な環境に適応しているため、高温に対して非常に敏感であり、将来の気候下では収量に深刻な影響が予想され、生産量が大幅に減少する可能性がある。コムギの高温ストレスに対する応答を理解するためには、キャノピー温度に影響する微気象要因の包括的な調査が不可欠である。しかし、高温乾燥環境におけるコムギの微気候に関する既存の知見は、限定的である。そこで本研究では、このギャップを埋めるため、スーダンの灌漑コムギ栽培における微気候の理解を深めることを目的とした。具体的には、高温乾燥条件下におけるキャノピー温度の品種間差を調査し、エネルギー収支の特徴を明らかにした。

先ず、2 つの高収量性・耐暑性コムギ品種 Imam と Bohaine の高温乾燥環境に対する応答を評価した。スーダンのゲジラ計画灌漑地において、2020/21 年の作期に隣接する 2 つの圃場で微気象観測を実施し、2m 高とキャノピーレベルで 1 時間ごとの微気象データを収集し、特にキャノピー温度低下（CTD）とその影響要因を調査した。微気象観測の結果、キャノピー表面温度とキャノピーレベルの気温に顕著な差があることが明らかになった。前者は蒸発冷却効果により一貫して低かったが、後者は主に対流と放射によるもので、キャノピー上部の特徴的な熱交換を反映していた。半ほふく性の Imam は立性の Bohaine よりも CTD が大きく、これは Imam が冷却能力に優れ、熱ストレスに対する脆弱性が低いことを示唆している。この冷却効果は、すべての重要な生育期間（栄養生長、出穂、登熟）において日中だけでなく、夜間にも及んだ。気温勾配は水蒸気圧勾配と負の相関があり、その相関は風速が低い夜間に強かった。これは、風速が熱と水蒸気の乱流によってコムギキャノピー周辺の微気候を変化させる決定的な影響を持つことを示唆している。さらに、2 品種間のキャノピー温度の差は、葉面積指数と地上部バイオマスの指標である NDVI の有意差に起因しており、品種によって高温に対する適応メカニズムが異なり、微気候を変化させる能力が高いことが示唆された。

次に、高温乾燥環境に対する灌漑コムギの応答および微気候に対する灌漑の影響を明らかにするために、スーダン北部・ドンゴラのコムギ圃場において、2021/22 年と 2022/23 年の 2 作期に正味放射（Rn）、地中熱フラックス（G）、土壌水分、2m 高とキャノピーレベルの温度・湿度を測定し、ボーエン比法を用いて潜熱フラックス（LE）と顕熱フラックス（H）を算出した。近隣の気象観測所の気温と比較した結果、圃場の気温がより低く、灌漑は微気候に大きな影響を与えることがわかった。コムギのキャノピーは、十分に灌漑された農地によって局所的な冷却効果を示したが、冷却効果の程度は生育期によって異なった。最も顕著な冷却効果は、栄養生長後期から生殖生長初期にかけて観測され、その差は 5℃以上であった。この差は、作物が完全なキャノピー被覆に達した後に大きくなったが、これはエネルギー収支の主成分が H や G で

はなく LE であったためである。したがって、灌漑は乾燥地域における熱ストレスの負の影響を緩和し、作柄を向上させる上で重要な役割を果たすと考えられる。本研究で得られた重要な情報は、微気候の変化を理解する上でのギャップを埋めるものであり、コムギの収量を向上させるための適応策に利用することができる。さらに、G と土壌条件との関係から、G は栄養生長後期と生殖生長初期には低く、栄養生長初期と生殖生長後期には高いことが示された。これらの知見は、土壌－作物－大気連続系のエネルギー分配の理解を深めるだけでなく、地熱フラックスの季節変動を明確に示すものである。

本論文は、特に高温で乾燥した環境下のコムギ栽培における微気候とエネルギー収支に関する理解を深める知見を示すものである。第一に、微気象学的アプローチを用いて、2 つのコムギ品種間のキャノピー温度の有意差を明らかにし、このようなデータ分析に生育習性を組み込むことの重要性を示した。第二に、高温乾燥環境における灌漑コムギを探究し、特に重要な生育期における特徴的なキャノピー温度変化を明らかにした。第三に、十分に水を与えたコムギのキャノピーが局所的な冷却効果をもたらす可能性を明らかにした。さらに、エネルギー収支における顕熱移流の重要な役割と、潜熱フラックス、正味放射、および周囲条件との複雑な関係を明らかにした。これらは、コムギ栽培における作物と微気候の相互作用に関する理解を深めるだけでなく、高温乾燥環境に適応した気候変動に強い農法を開発するための貴重な知見を提供するものである。

結論として、本論文の意義は次のように要約できる。品種固有の微気象応答を作物モデルに組み込むことにより、モデル精度が向上し、多様な環境条件下での作物の発育、生長、収量について、より信頼性の高いシミュレーションが可能になる。微気象学的アプローチを特定の品種に適合させることで、作物と微気候の相互作用において重要な生理学的・形態学的形質を捉えることができ、精度が向上する。さらに、キャノピー構造や葉面積などの形質に焦点を当てた育種戦略は微気象条件の最適化に合致する。このことから、特定の微気候に調和する品種固有の形質を識別することは、様々な気候的課題に対する耐性に関連する形質について、的を絞った選抜を可能とし、多様な環境条件に耐えるコムギ品種の開発につながる。したがって、微気象学的知見を作物モデリングと植物育種の両方に応用することは、スーダンの高温乾燥環境において気候変動に強く生産性の高い農業を推進する上で重要である。

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List of publications

1. Title: Micrometeorological Comparison of Canopy Temperature between Two Wheat Cultivars Grown under Irrigation in a Hot Environment in Sudan

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