available at www.sciencedirect.com
SCIENCE DIRECT
journal homepage: www.elsevier.com/locate/agwat

Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain

Hai-Jun Liu [a,b], *Yaohu Kang* [a,*]

[a] *Key Lab of Water Cycle and Related Land Surface Process, Institute of Geographic Sciences and Natural Resources Research, CAS, Datun Road, Jia 11, Beijing 100101, China*
[b] *China Agricultural University (East campus), P.O. Box 151, Qinghua Donglu 17#, Beijing 100083, China*

ARTICLE INFO

Article history:
Accepted 15 January 2006

Keywords:
Sprinkler irrigation
Microclimate
Air temperature
Vapor pressure deficit
Water surface evaporation

ABSTRACT

Sprinkler irrigation, as one of the useful technologies to increase crop production and water use efficiency, has been extensively used in the North China Plain. However, few researches related to the season-long microclimatic changes under sprinkler irrigation in this region. A field experiment was carried out to investigate the long-time effect of sprinkler irrigation on microclimate in a winter wheat (*Triticum aestivum* L.) field and compare the microclimate under both sprinkler and surface irrigation conditions from April 2001 to June 2003 in two experimental stations in the North China Plain. Results showed that air temperature, air temperature gradient from 1 to 2 m above ground surface and vapor pressure deficit (VPD) were significant lower ($P < 0.05$) in the sprinkler-irrigated field with respect to those in surface irrigation field after the first sprinkler irrigation during three winter wheat seasons. The maximum reduction in air temperature and VPD in the sprinkler-irrigated field in comparison with the surface irrigated field occurred on sprinkler irrigation days. During daytime (between 08:00 and 20:00 h), air temperature and VPD were significantly affected by sprinkler irrigation respected to night-time (between 20:00 and 08:00 h) at sprinkler irrigation intervals. Cumulative water surface evaporation, measured by using a standard pan (20 cm in diameter) placed at the top of canopy, was about 3–11% lower in the sprinkler-irrigated field respected to in the surface irrigated field from April 11 to June 4 in the three seasons. The reduction in values of difference in air temperature, vapor pressure deficit and pan evaporation in the sprinkler-irrigated field in comparison with surface irrigated field were bigger when it was hot, dry and windy with concentrated precipitation.

1. Introduction

The North China Plain (NCP), one of China's most important agricultural regions, produces 19% of the nation's food and 42% cotton (Wang et al., 2001; Zhang et al., 2003). Because of monsoon influence, rainfall is highly variable in this region. Mean annual precipitation is 500–600 mm, a majority of which occurs between June and September (Zhang et al., 2004). Annual crop actual evapotranspiration of 800–900 greatly exceeds the annual precipitation (Liu et al., 2002). Therefore, traditional irrigation techniques such as surface irrigation have been used to maintain and enhance crop growth and yield in this region (Chen et al., 2003; Mao et al., 2003; Wang et al., 2004). On the other hand, recent work (Liu et al., 2003; Sun et al., 2004) has demonstrated surface irrigation to inefficiently direct water and fertilizer amendments to crop

* *Corresponding author*. Tel.: +86 10 64856516; fax: +86 10 64856516.
E-mail addresses: shanxilhj@yahoo.com.cn (H.-J. Liu), kangyh@igsnrr.ac.cn (Y. Kang).
0378-3774/$ – see front matter
doi:10.1016/j.agwat.2006.01.015

Table 1 – Sprinkler and surface irrigation dates and water amount in 2001, 2002 and 2003 experimental seasons

Seasons	Irrigation methods	March		April					May					Total water amount applied (mm)
		1	27	3	9	16	21	28	1	4	9	16	21	
2000–2001	Sprinkler irrigation	–	–	63	–	–	60	–	–	–	40	30	30	223
	Surface irrigation	–	–	128	–	–	–	128	–	–	–	–	–	256
2001–2002	Sprinkler irrigation	40	30	–	–	40	–	–	40	–	–	–	–	150
	Surface irrigation	130	–	–	–	114	–	–	–	–	–	–	–	244
2002–2003	Sprinkler irrigation	–	–	–	40	–	50	–	–	48	–	–	49	187
	Surface irrigation	–	–	–	118	–	–	–	–	91	–	–	93	302

root zones by non-uniformity soil water distribution and great fluctuation of soil water content at irrigation intervals.

Alternative irrigation systems such as sprinkler irrigation, is an advanced irrigation technique for water-saving and fertigation and in accurately controlling irrigation time and water amount (Li and Rao, 2003), has been used in the NCP. The area irrigated by sprinkler irrigation increased from 46,000 ha in 1989 to 2,634,000 ha in 2003. Study on winter wheat showed that crop yield and water use efficiency in sprinkler-irrigated fields was higher than that in surface irrigated fields (Yang et al., 2000). The result of high crop yield and water use efficiency in sprinkler-irrigated field is partly because sprinkler irrigation can produce a favorable microclimate for crop growth. Tolk et al. (1995) found sprinkler irrigation resulted in crop transpiration reduction by more than 50% during irrigation process. The increasing in photosynthesis rate and reduction in leaf respiration rate at night also has been found in sprinkler-irrigated area (Chen, 1996; Yang et al., 2000).

In the past several decades, many studies have been carried out all over the world for investigating water evaporation and the microclimate change pattern of the sprinkler-irrigated field. During sprinkler irrigation, water evaporation were from droplets, canopy interception and wet soil surface (Frost and Schwalen, 1955; Dylla and Shull, 1983; Norman and Campbell, 1983; Steiner et al., 1983; Kohl et al., 1987; Walter, 1988; Ayars et al., 1991; Thompson et al., 1997; Li and Rao, 2000; Tarjuelo et al., 2000). The evaporation process cools the droplets, enabling heat to be drawn from the air through which the droplets pass and add water vapor to the atmosphere (Kohl and Wright, 1974). Thompson et al. (1993b) found that direct evaporation of water droplets is less than 1% of total water applied. However, a total amount of energy equivalent to 24% of the net radiation during sprinkler irrigation transferred from plant environment to the water droplets as they were warmed during flight and after they affected the canopy and soil. By studying the downwind effect of droplets evaporation for sprinkler spray, Kohl and Wright (1974) showed that the air temperature generally reduced less than 1 °C and vapor pressure increased by 0.8 hPa. Tolk et al. (1995) found that vapor pressure deficit (VPD) and air temperature in canopy decreased significantly during and following sprinkler irrigation. Thompson et al. (1993b) indicated that air temperature above canopy in the irrigated area was decreased quickly with 4–7 °C lower than that outside the irrigated area in the first 10 min after the start of sprinkler irrigation. Meanwhile, dry bulb temperature above the canopy of the corn was approximately the same as that outside the irrigated area in 60 min after irrigation. Chen (1996) found that the average daytime vapor pressure and relative humidity increased, while soil temperature and canopy temperature decreased in the sprinkler-irrigated mulberry field. Some models were also developed to simulate field microclimate under sprinkler irrigation (Washington and Larry, 1988a,b; Thompson et al., 1993a,b). Based on the relationship between sprinkler and field microclimate, spraying a small amount of water (from 1.0 to1.5 mm water) by using sprinkler irrigation system also has been studied to regulate field microclimate for dry-hot-wind protection (Liu et al., 2004). However, to our knowledge, all researches in the available present literatures were about the field microclimate changes during the period of sprinkler

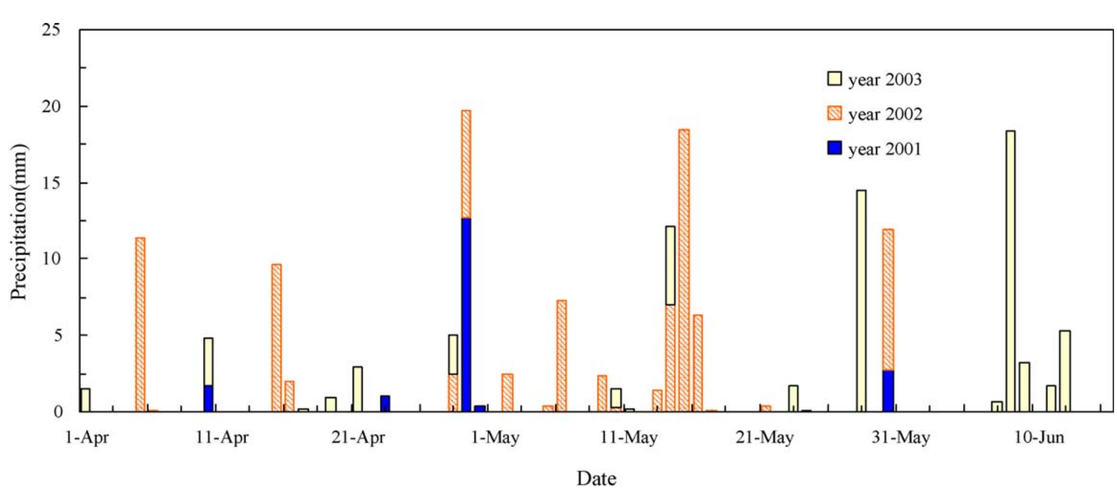

Fig. 1 – Precipitation distribution from April 1 to winter wheat harvest day in 2001, 2002 and 2003.

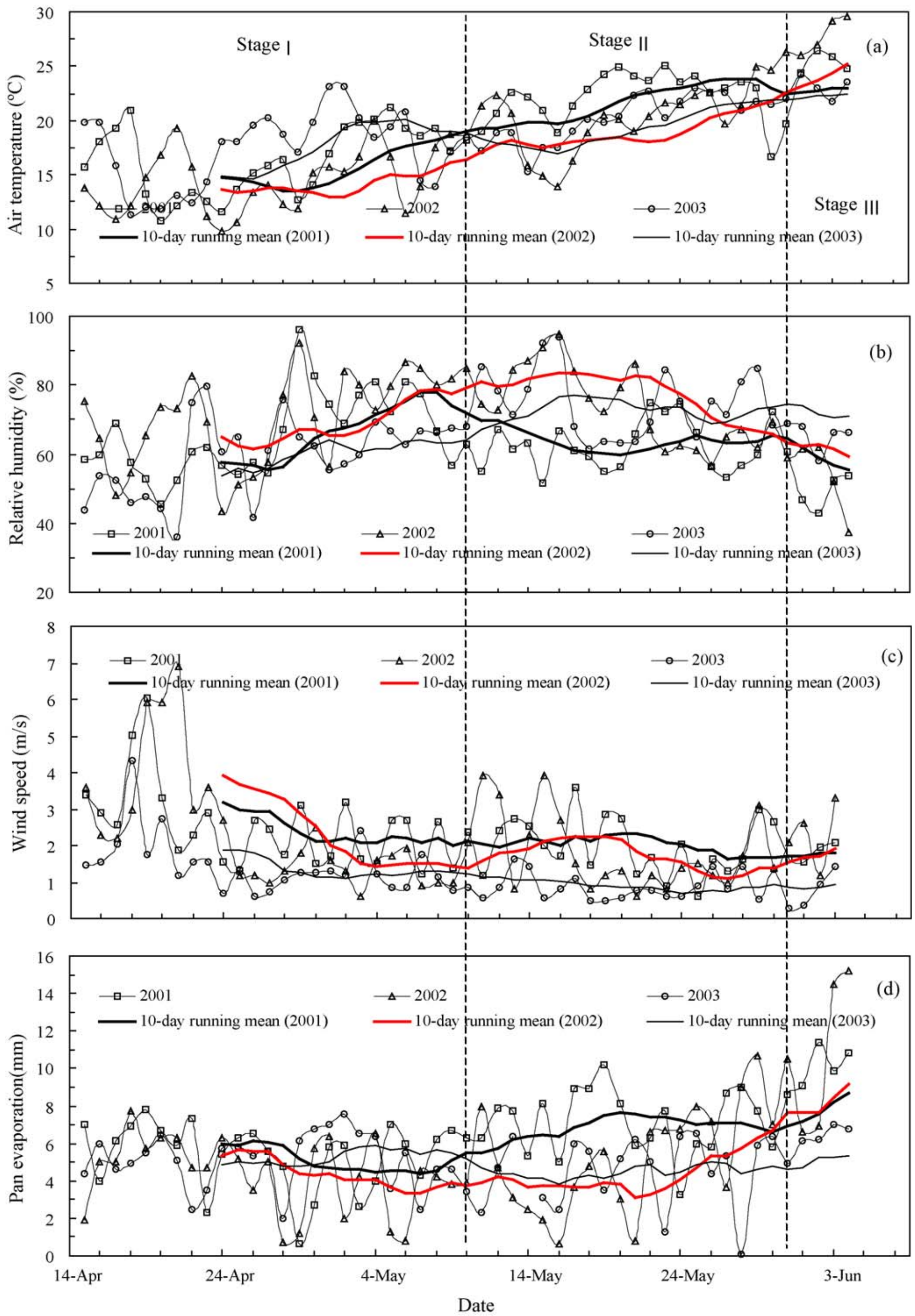

Fig. 2 – Air temperature (a), relative humidity (b) and wind speed (c) at height of 2 m above ground surface and water surface evaporation (d) measured using standard 20 cm diameter pan installed on the top of canopy in surface irrigation field during the period between April 14 and June 4 in 2001, 2002 and 2003.

irrigation or a very short period after sprinkler. Therefore, further research is needed to study long-time effect of sprinkler irrigation on field microclimate, especially in crop growing season. In additional, only a few researches are related to compare the air temperature and vapour pressure in sprinkler-irrigated field and the non-irrigated field, few studies were focused on comparison of microclimate pattern between the fields with sprinkler irrigation and the fields with surface irrigation.

The objective of this study was to compare the long-time effect of sprinkler and surface irrigation on field microclimate during three winter wheat growth seasons.

Table 2 – Climatic variables and statistical analysis at three stages in 2001, 2002 and 2003 experimental seasons

Seasons	Temperature (°C)			RH (%)			Wind speed (m/s)			E_{pan} (mm/d)		
	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003
Stage I	15.7 ab	15.0 a	16.9 b	64.9 a	69.9 a	58.1 b	2.5 b	2.5 b	1.5 aB	5.4 a	4.9 a	5.3 a
Stage II	22.3 b	20.1 a	20.2 a	62.4 a	73.7 b	74.7 b	2.0 b	1.8 b	0.9 aA	7.1 b	5.2 a	4.6 a
Stage III	24.2 a	27.6 b	22.9 a	51.3 a	54.0 b	65.5 c	2.1 b	2.8 b	0.9 aA	10.0 b	10.7 b	6.2 a

Within each line means of air temperature, relative humidity (RH), wind speed and pan evaporation (E_{pan}) with different lowercases are significantly different at $P < 0.05$ levels. Within column of wind speed in 2003, means with different capital letters are significantly different at $P < 0.05$ levels.

2. Materials and methods

2.1. Experiment site

Field experiments were conducted during three succinct growing seasons October 20, 2000 to June 8, 2001 (the first season), October 11, 2001 to June 8, 2002 (the second season), and October 16, 2002 to June 13, 2003 (the third season). Experiments during the first and second seasons were conducted at the Yucheng Comprehensive Experimental Station (YCES) Shandong Province, China (latitude 36°57′N, longitude 116°36′E; 20 m above sea level). The mean annual temperature is 13.1 °C and the mean annual precipitation is 582 mm. The experiment in the third season was conducted at the Tongzhou Experimental Base for Water-Saving Irrigation Research (TEB), Beijing, China (latitude 39°36′N, longitude 116°48′E; 20 m above sea level). The mean annual temperature at TEB is 11.2 °C and the mean annual precipitation is about 550 mm. YCES and TEB, both located in the North China Plain, experience temperate and semi-humid conditions with 70% of the precipitation concentrated between July and September and a dry season occurring during the spring and early summer.

2.2. Experiment design

The experimental field in the first and second season, measuring 144 m × 108 m, was fitted with a solid set sprinkler irrigation system consisting of six laterals with full circle impact sprinklers (ZY2, made in China) mounted on 1.30 m risers. Eight sprinklers were connected to each lateral with lateral and nozzle spaces 18 m apart. The sprinkler intensity was 10.0 mm/h with two laterals operating at the same time. A surface irrigation field, measuring 200 m × 108 m in the south-west of the sprinkler-irrigated field was the control. The basin size of the surface irrigation field was about 70 m × 8 m, similar size as local experience. In the first season, winter wheat was sown on October 27 and 28 in 2000 at a row spacing

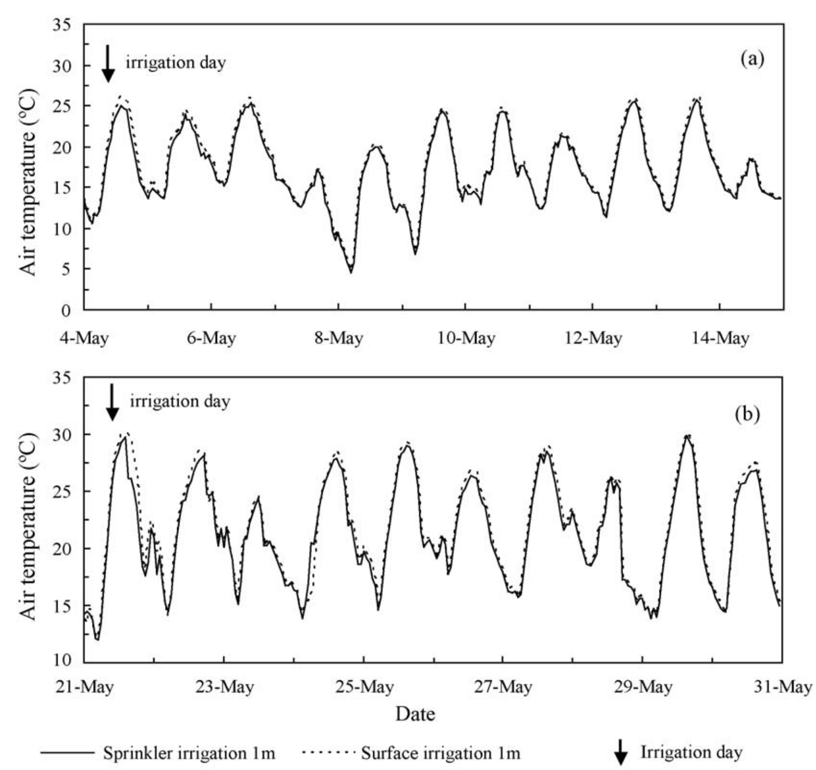

Fig. 3 – Daily temperature patterns at 1 m height in sprinkler and surface irrigated fields at two sprinkler irrigation intervals in 2003, sprinkler irrigations and surface irrigations stopped at the same time on May 4 and 21, 2003.

Table 3 – Reduced values of air temperature (°C) at 1 m height averaged over daytime (between 08:00 and 20:00 h) and night-time (between 20:00 and 08:00 h) in the sprinkler-irrigated field respected to surface irrigated field at two sprinkler irrigation intervals in 2003

Irrigation intervals		Days after sprinkler										
		0	1	2	3	4	5	6	7	8	9	10
First irrigation interval, between May 4 and 14	Daytime	1.05 c	0.71 c	0.54 c	0.19	0.27	0.15	0.17	0.20	0.45 c	0.48 c	0.17
	Night-time	0.50 b	0.36 a	0.18	0.19	−0.01	0.34	0.08	0.10	0.15	0.22	0.00
Second irrigation interval, between May 21 and 30	Daytime	2.86 c	0.48 b	0.19	0.35	0.18	0.48 b	0.45 b	0.31 b	0.20	0.58 b	
	Night-time	0.56 b	0.16	0.16	0.42 b	0.22	0.27	0.28	0.16	0.22	0.27	

Within the first line, numbers of 0–10 represent on sprinkler irrigation days and days from 1 to 10 after sprinkler irrigation. Means with lowercases of "a", "b" and "c" are significantly different between in the sprinkler-irrigated field and surface irrigated field at $P < 0.05$, 0.01 and 0.001 levels, respectively.

of 0.18 m and sowing rate of 150 kg/ha. The crop was harvested on June 4 and 8 in 2001 in the surface and sprinkler irrigation fields, respectively. In the second season, winter wheat was sown from October 11 to 13, 2001 at a row spacing of 0.24 m and sowing rate of 150 kg/ha. The crop was harvested on June 5 and 8 in 2002 for surface and sprinkler irrigation treatments, respectively.

During the third season, the experiment was conducted on a sprinkler-irrigated field measuring 240 m × 208 m. The field was irrigated using the same configuration as in the first two seasons. A surface irrigation field, measuring 208 m × 160 m in the east side of the sprinkler-irrigated field, was used as the control. The basin size of the surface irrigation field was 50 m × 5 m. Winter wheat was sown on October 16, 2002 at a row spacing of 0.15 m and sowing rate of 375 kg/ha. The crop was harvested on June 13, 2003.

2.3. *Irrigation and observations*

2.3.1. *Irrigation*

Soil water content from ground surface to the depth of 1.40 m was measured at intervals of 0.10 m every 5 days using neutron probe access tubes at three points in the sprinkler and surface irrigated fields in the first and second season. In the third season, soil water potential was measured using mercurial tensiometers at depths of 0.10, 0.20, 0.30, 0.40, 0.50, 0.70, 0.90, 1.20, 1.50 and 1.80 m at three locations in sprinkler and surface irrigated fields.

Sprinkler irrigation in the first and second seasons started when mean volumetric soil water content (SWC) in a 0.6-m depth soil layer was smaller than 60% field capacity (FC). The surface irrigation was scheduled based on the local experience. Sprinkler irrigation in the third season started when the

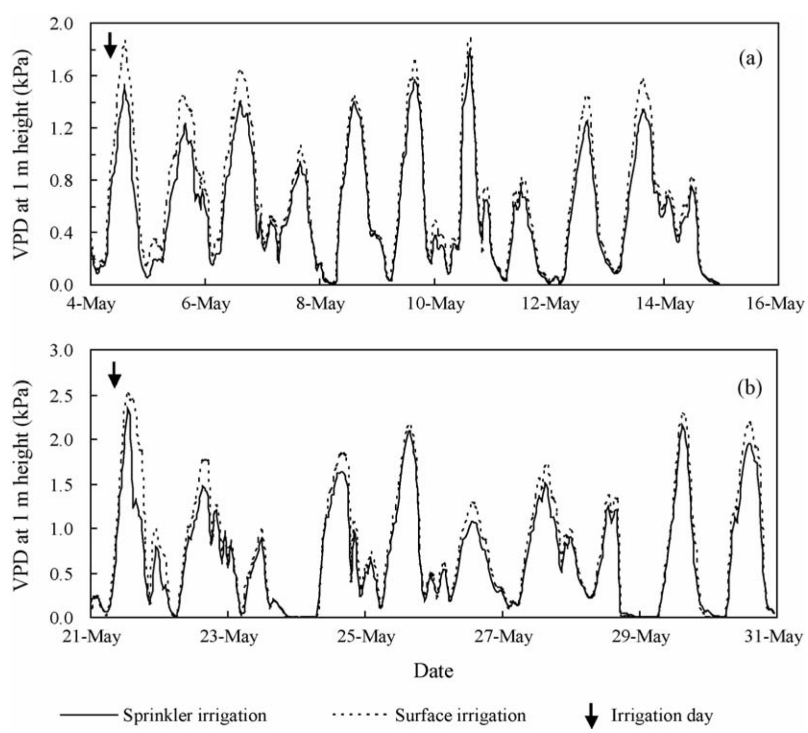

Fig. 4 – Daily patterns of vapor pressure deficit (VPD, kPa) at height of 1 m in sprinkler and surface irrigated fields at two sprinkler irrigation intervals in 2003, sprinkler irrigations and surface irrigations stopped at the same time on May 4 and 21, 2003.

mean soil potential within the 0.60 m depth was smaller than −45 kPa (equivalent to 56% FC). To compare field microclimate in the sprinkler and surface irrigated fields under the same climatic conditions, both irrigations stopped at the same time in the third season except on April 21, 2003.

From March 1 to June 15, winter wheat irrigation times for sprinkler and surface irrigation were as follows, five to two in the first season, four to two in the second season, and four to three in the third season, respectfully (Table 1). The total irrigation water amounts were 223 and 256 mm for the sprinkler and surface irrigated fields in the first season, respectively, 150 and 244 mm in the second season, and 187 and 302 mm in the third season, respectively. Sprinkler irrigation frequency was higher, while total irrigation water was smaller in the sprinkler-irrigated field than in the surface irrigated field in the three experimental seasons. Sprinkler irrigation always characterizes by higher frequency with smaller quota for each event respected to surface irrigation.

2.3.2. *Observations*

During the first season, an automatic microclimatic station (AMS) was installed at the center of both sprinkler and surface irrigated fields, to measure mean hourly wind speed (three-cup anemometer, Model VF-1, made in China) and wet and dry bulb temperatures (aspirated psychrometer with radiation shield, Model HTF-2, made in China) at four heights, 0.5, 1.0, 2.0 and 4.0 m from March 18 to June 8, 2001. On April 16, the sensors' heights were adjusted to 1.0, 2.0, 3.0 and 4.0 m above ground surface because the average plant height of winter wheat had already exceeded 0.5 m. In the second season, climatic data was recorded from April 10 to June 8, where sensors were installed at 1.0, 2.0, 3.0 and 4.0 m above ground surface throughout the experimental period. Climatic sensors were installed at 1.0, 2.0, 4.0, 6.0 and 8.0 m above ground surface from April 6 to June 13 in the third season. DT500 dataTakers (DataTaker Pty Ltd., made in Australia) were used to record microclimatic data. Field actual vapor pressure was calculated as follows:

$$e = e_{t_w} - AP(t - t_w) \quad (1)$$

where t and t_w are temperatures of dry bulb and wet bulb in °C, respectively; e is actual vapor pressure in kPa; e_{t_w} is saturate vapor pressure at temperature of t_w in hPa, determined by (Allen et al., 1998)

$$e_{t_w} = 0.6108 \exp\left(\frac{17.27 t_w}{t_w + 237.3}\right) \quad (2)$$

where exp (…) is 2.7183 (base of natural logarithm) raised to the power (…); A is the psychrometric coefficient (0.667×10^{-3} °C^{-1}) and P is the atmospheric pressure in kPa at experimental stations. Vapor pressure deficit (VPD) was calculated by

$$\text{VPD} = e_t - e \quad (3)$$

where e_t is saturated vapour pressure at air temperature in kPa, determined from Eq. (2) by substituting air temperature (t) for t_w.

Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evapora-

Table 4 – Reduced values of vapor pressure deficit (VPD, kPa) at 1 m height averaged over daytime (between 08:00 and 20:00 h) and night-time (between 20:00 and 08:00 h) in the sprinkler-irrigated field respected to surface irrigated field at two sprinkler irrigation intervals in 2003

Irrigation intervals		Days after sprinkler										
		0	1	2	3	4	5	6	7	8	9	10
First irrigation interval, between May 4 and 14	Daytime	2.77 c	2.26 c	1.89 c	0.56 c	0.33 b	0.53 a	0.60 b	0.61 c	1.43 c	1.59 c	0.29
	Night-time	2.16 c	2.38 c	1.28 c	0.04	−0.06	−1.14	−0.91	0.02	0.99 c	0.64 c	−0.11
Second irrigation interval, between May 21 and 30	Daytime	3.95 c	1.65 b	0.27	0.88 a	0.50 a	1.31 c	1.55 c	0.54 a	0.81 a	1.69 c	
	Night-time	1.14 a	0.31	−0.05	0.66 a	0.21	0.24 a	0.51 a	−0.13	−0.07	−0.21	

Within the first line, numbers of 0–10 represent on sprinkler irrigation days and days from 1 to 10 after sprinkler irrigation. Means with lowercases of "a", "b" and "c" are significantly different between in the sprinkler-irrigated field and surface irrigated field at $P < 0.05$, 0.01 and 0.001 levels, respectively.

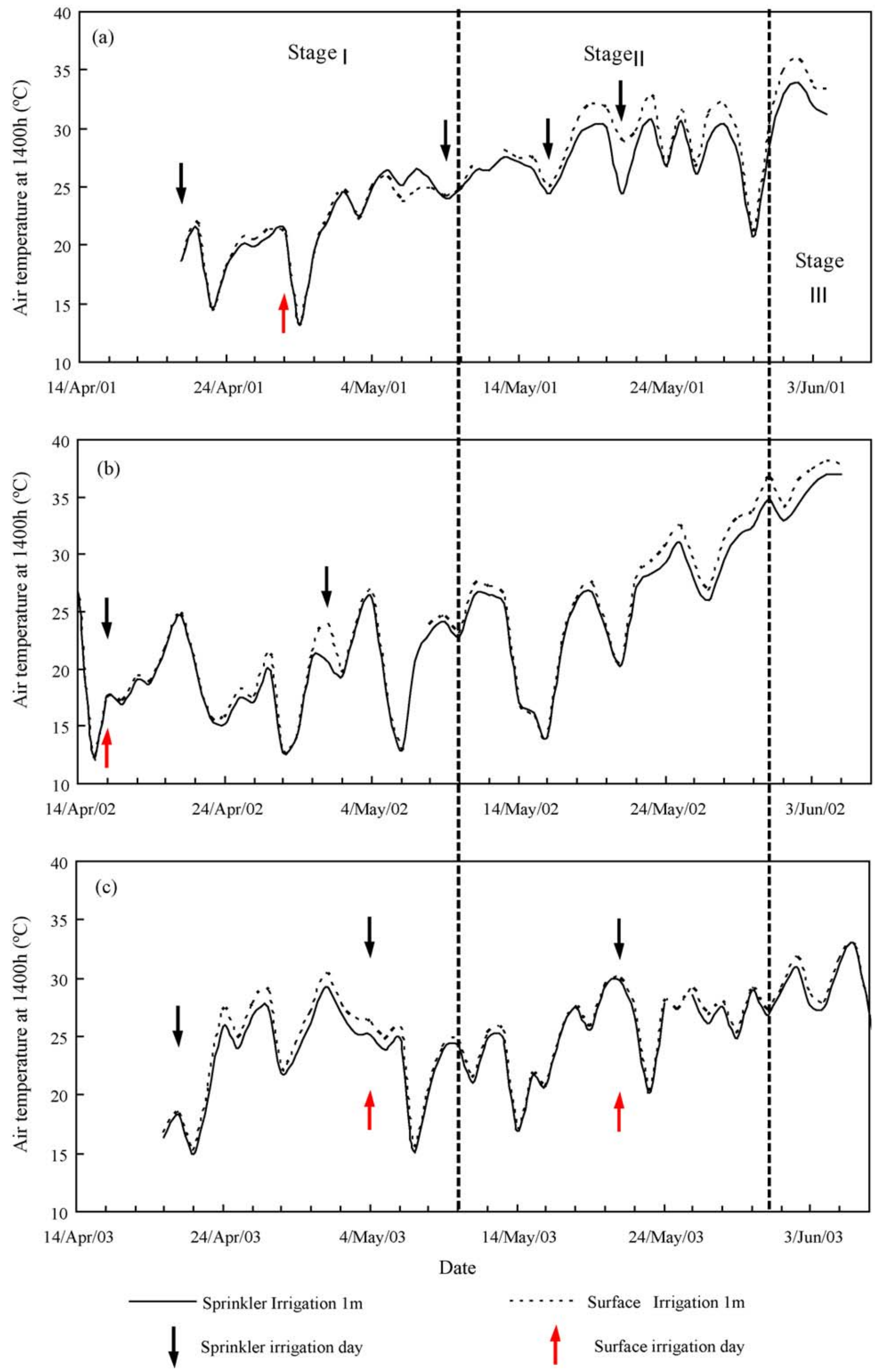

Fig. 5 – Air temperature at 1 m height above ground surface measured at 14:00 h in sprinkler and surface irrigated fields from April 14 to winter wheat harvest day in 2001 (a), 2002 (b) and 2003 (c).

tion from an open water surface (Allen et al., 1998). Twenty centimeter diameter pan installed on the top of canopy near AMS was used to measure free water surface evaporation (E_{pan}) in order to examine the comprehensive change of field microclimate in all of the three experimental seasons. The height of the 20 cm pan was adjusted above the top of canopy, which is similar to the approach used in tomato and potato field experiments (Yuan et al., 2001; Kang et al., 2004). E_{pan} was measured at 08:00 h daily from March 18 to June 8 in 2001, from March 23 to June 8 in 2002, and from April 10 to June 13 in 2003 for the first, second and third seasons, respectively.

Table 5 – Statistical analysis on reduced values of maximum and mean daily temperature and vapor pressure deficit (VPD) at 1 m height, air temperature gradient from 1 to 2 m height and pan evaporation (E_{pan}) measured using standard 20 cm pans placed on the top of canopy in the sprinkler irrigated field respected to surface irrigated field at the three stages in the three experimental seasons

Winter wheat growth seasons	Stages	Reduced values in the sprinkler-irrigated field respected to surface irrigated field averaged at three stages and/or seasons, respectively					
		Daily maximum temperature (°C)	Daily average temperature (°C)	Daily maximum VPD (kPa)	Daily average VPD (kPa)	Air temperature gradient at 14:00h (°C)	Daily E_{pan} (mm/d)
2000–2001	Stage I	−0.15	−0.05	0.133	0.059	0.15	0.69 c
	Stage II	1.11 c	0.29 c	0.464 c	0.168 c	0.85 c	
	Stage III	1.87 c	1.12 c	0.852 c	0.425 c	1.08 b	
	All season	0.69 c	0.21 b	0.413 c	0.17 c	0.53 c	
2001–2002	Stage I	0.22 b	−0.08	0.090 a	0.055	0.40 a	0.29 b
	Stage II	0.74 c	0.25 c	0.211 c	0.095 c	0.53 c	
	Stage III	1.43 b	0.68 b	0.409 a	0.150 b	0.80 b	
	All season	0.73 c	0.18 a	0.216 c	0.10 c	0.66 c	
2002–2003	Stage I	0.78 c	0.23 c	0.190 c	0.063 c	0.48 c	0.14
	Stage II	0.33 c	0.21 b	0.097 c	0.008	0.20	
	Stage III	0.63 a	0.64 a	0.061	0.010	0.65 c	
	All season	0.59 c	0.36 c	0.172 c	0.09 c	0.38 c	

Within columns means with lowercases of "a", "b" and "c" at stages of I, II, III and all season are significantly different among the three years at $P < 0.05$, 0.01 and 0.001 levels, respectively.

3. Results

3.1. Climatic condition

The total precipitation from April 1 to June 15 in 2001, 2002 and 2003 was 18.6, 88.5 and 63.0 mm, respectively, which was attributed to 6, 18 and 16 rainfall events, respectively (Fig. 1). Frequency of rain from April 1 to June 15 were the highest but non-uniformly distributed in 2002, the lowest in 2001, and uniformly distributed in 2003.

To illustrate the rules of effect of sprinkler irrigation on field microclimate under different climatic conditions, the experimental period was divided into three stages according to climatic condition (Fig. 2). The first stage (Stage I) was from April 14 to May 10, the second stage (Stage II) was from May 10 to 31, and the third stage (Stage III) was from May 31 to June 4. The statistical analysis on climatic variables in three seasons was shown in Table 2.

At Stage I in 2003, air temperature was the highest and relative humidity (RH) the lowest, creating relative hot and dry conditions respected to 2001 and 2002; at Stage II in 2001, air temperature was the highest and relative humidity (RH) the lowest creating hot and dry conditions relative to 2002 and 2003; at Stage III, temperature was the highest in 2002 and RH was lowest in 2001 respected to 2003, resulting in a lowest pan evaporation in 2003. Wind speed in 2001 and 2002 was insignificant difference, but was higher than 2003.

3.2. *Effect of sprinkler irrigation on diurnal courses of air temperature and vapor pressure deficit at sprinkler irrigation intervals*

Fig. 3 pictured diurnal course of air temperature at 1 m height in the sprinkler and surface irrigated fields at two sprinkler irrigation intervals when both irrigation events ceased on the same days. Air temperature in daytime (between 08:00 and 20:00 h) was generally lower in the sprinkler-irrigated field in comparison with the surface irrigated field at irrigation intervals, while it was not so much during time between 20:00 and 08:00 h. Air temperature in the daytime was significantly affected ($P < 0.01$) by sprinkler irrigation 2 or 3 days after the cessation of irrigation and the air temperature within night-time was significantly affected 1 or 2 days after irrigations ($P < 0.05$). Greater effect occurred during daytime in comparison with during night-time (Table 3). The maximum reduction in value of air temperature in the sprinkler-irrigated field occurred on irrigation day. Maximum reductions in temperature at 1 m height were 1.8 and 3.9 °C in the sprinkler-irrigated field respective to surface irrigated field from irrigation days of May 4 and 21 in 2003, respectively. Reduced values of air temperature in the sprinkler-irrigated field respected to the surface irrigated field decreased quickly with time. On day one after sprinkler irrigation, the maximum reduction in temperature in the sprinkler-irrigated field decreased to 1.1 and 0.9 °C with respective of surface irrigated field and then generally less than 1.0 °C in the other days at sprinkler irrigation intervals. The daily maximum reduction of air temperature generally occurred at 14:00 h, which is approximately the same time with daily maximum air temperatures appeared (Fig. 3). Mean reduction in value of air temperature during daytime at sprinkler irrigation intervals was a function of time after sprinkler irrigation and climatic variables, and was regressed using data from May 4 to 30 in 2003 as follows:

$$\Delta T = (-1.043 + 0.12T_{ave} - 0.01233RH_{ave} + 0.7012U_{ave})D^{-0.6326}, \quad (4)$$

$$R^2 = 0.67$$

where D is the number of days after sprinkler irrigation. The value of D is 1 on the sprinkler irrigation day. ΔT is reduction in value of air temperature at 1 m height averaged over daytime (between 08:00 and 18:00 h) on Dth day in the sprinkler-irrigated field in comparison with the surface irrigated field at sprinkler irrigation intervals when sprinkler and surface irrigations ceased on the same day, °C; T_{ave}, RH_{ave}, U_{ave} are mean daily air temperature (°C), relative humidity (%) and wind speed (m/s) at 2 m height on Dth day measured at meteorological stations, respectively.

Daily vapor pressure deficit at 1 m height in the sprinkler-irrigated field was smaller than in the surface irrigated field at two irrigation intervals when both sprinkler and surface irrigations ceased at the same time (Fig. 4). The effect of sprinkler irrigation on VPD was greatly different during daytime and night-time (Table 4). Within daytime, VPD was greatly

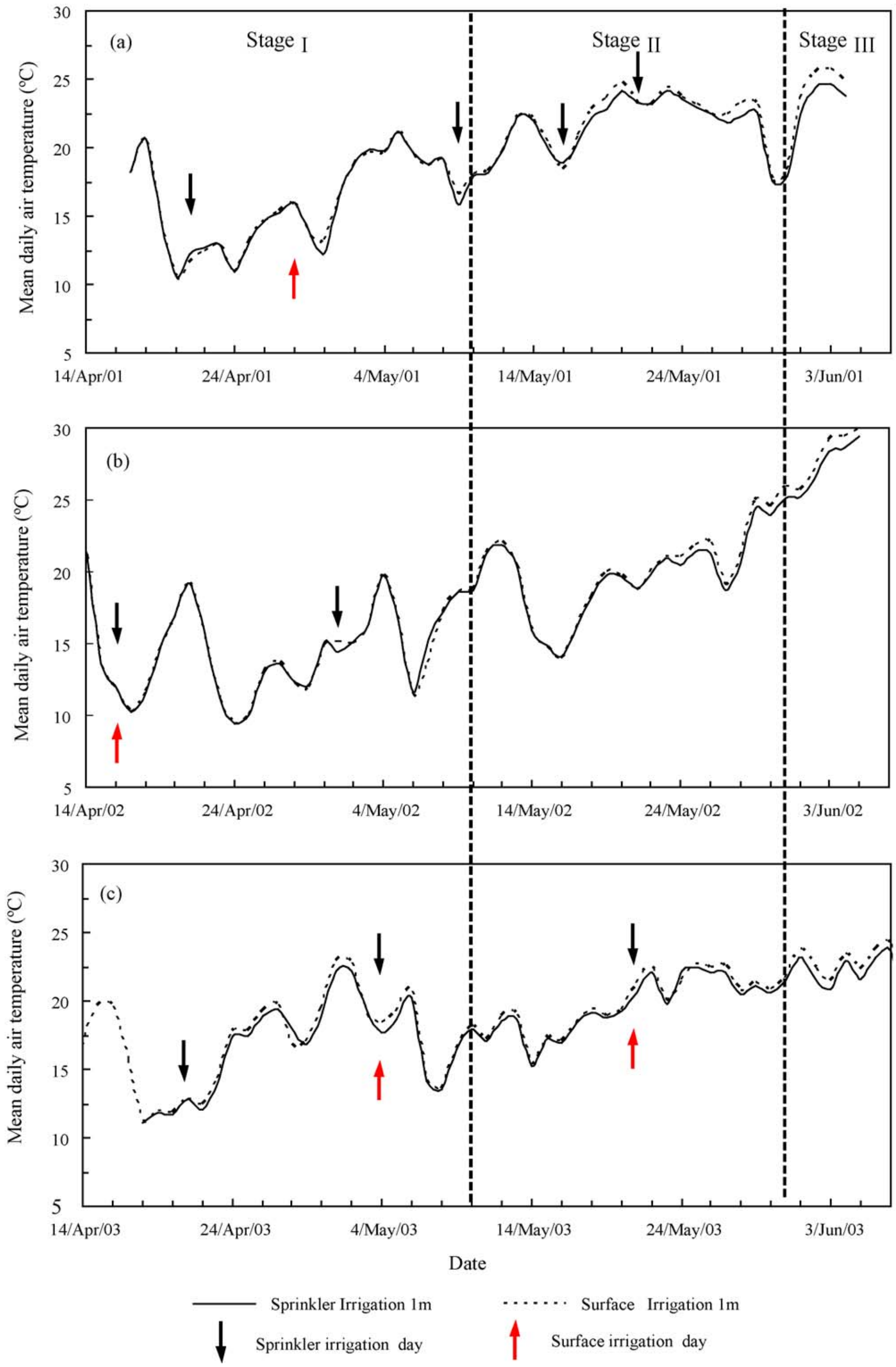

Fig. 6 – Daily average air temperature at 1 m height above ground surface in sprinkler and surface irrigated fields from April 14 to winter wheat harvest day in 2001 (a), 2002 (b) and 2003 (c).

affected by sprinkler irrigation throughout irrigation intervals, while the VPD within night-time was just significantly affected for the first 2 or 3 days after sprinkler irrigations (Table 4). The maximum reduction in daily VPD at 1 m height in the sprinkler-irrigated field in comparison with the surface irrigated field occurred on irrigation days. It was 0.44 and 1.20 kPa from irrigation days of May 4 and 21 in 2003, respectively. The reduced value of VPD decreased with time. On the first days after irrigations, the maximum reduction in daily VPD decreased by 0.33–0.38 kPa in the sprinkler-irrigated field respected to surface irrigated field. In other days at irrigation intervals, the reduced values of VPD in the sprinkler-irrigated field was generally less than 0.20 kPa but this effect was significant ($P < 0.05$) at sprinkler irrigation intervals (Table 4). The maximum reduction in daily VPD generally appeared at the same time with maximum daily VPD. This result was similar to

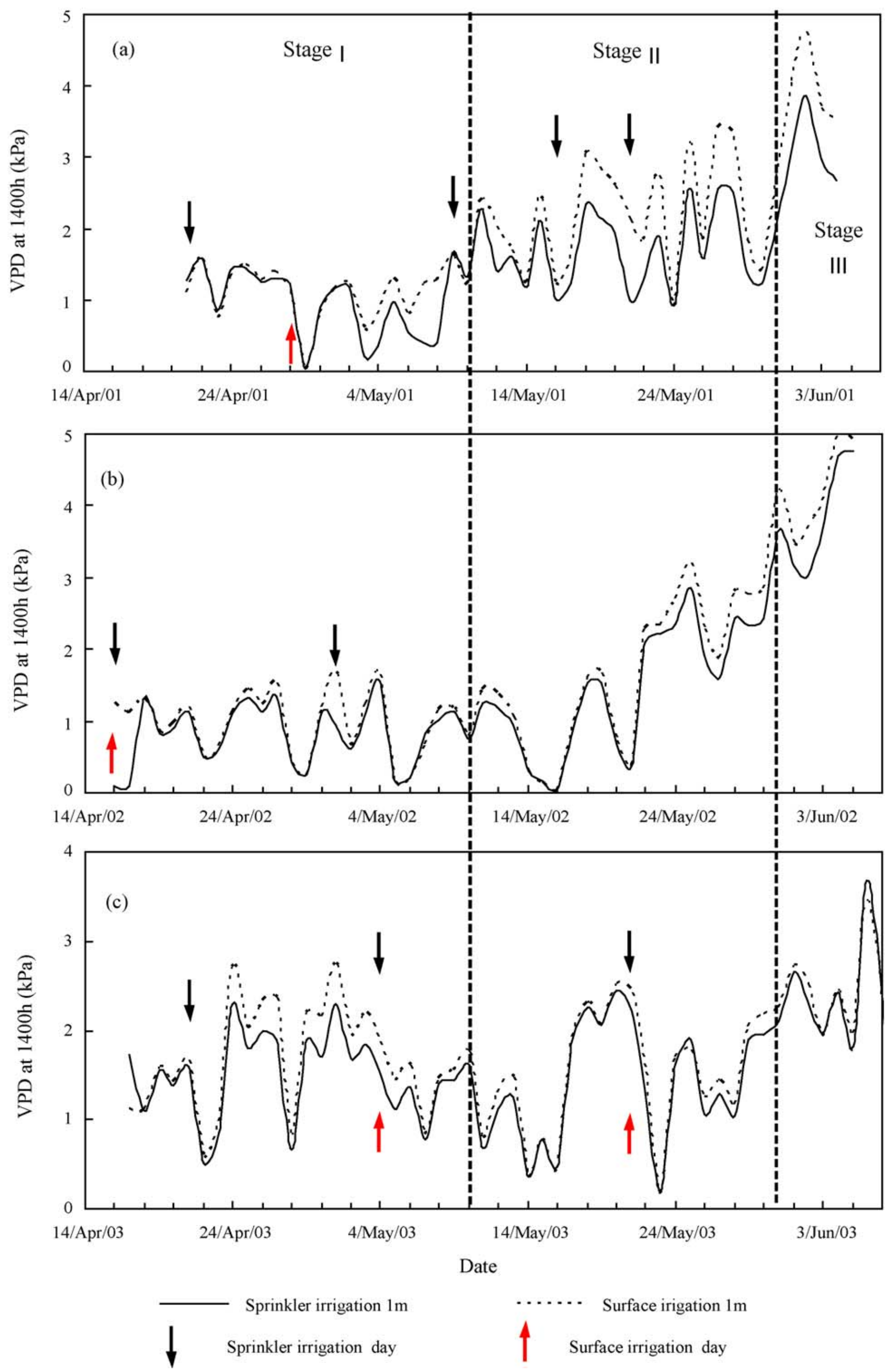

Fig. 7 – Vapor pressure deficit (VPD, kPa) of 1 m height above ground surface measured at 14:00 h in sprinkler and surface irrigated fields from April 14 to winter wheat harvest day in 2001 (a), 2002 (b) and 2003 (c).

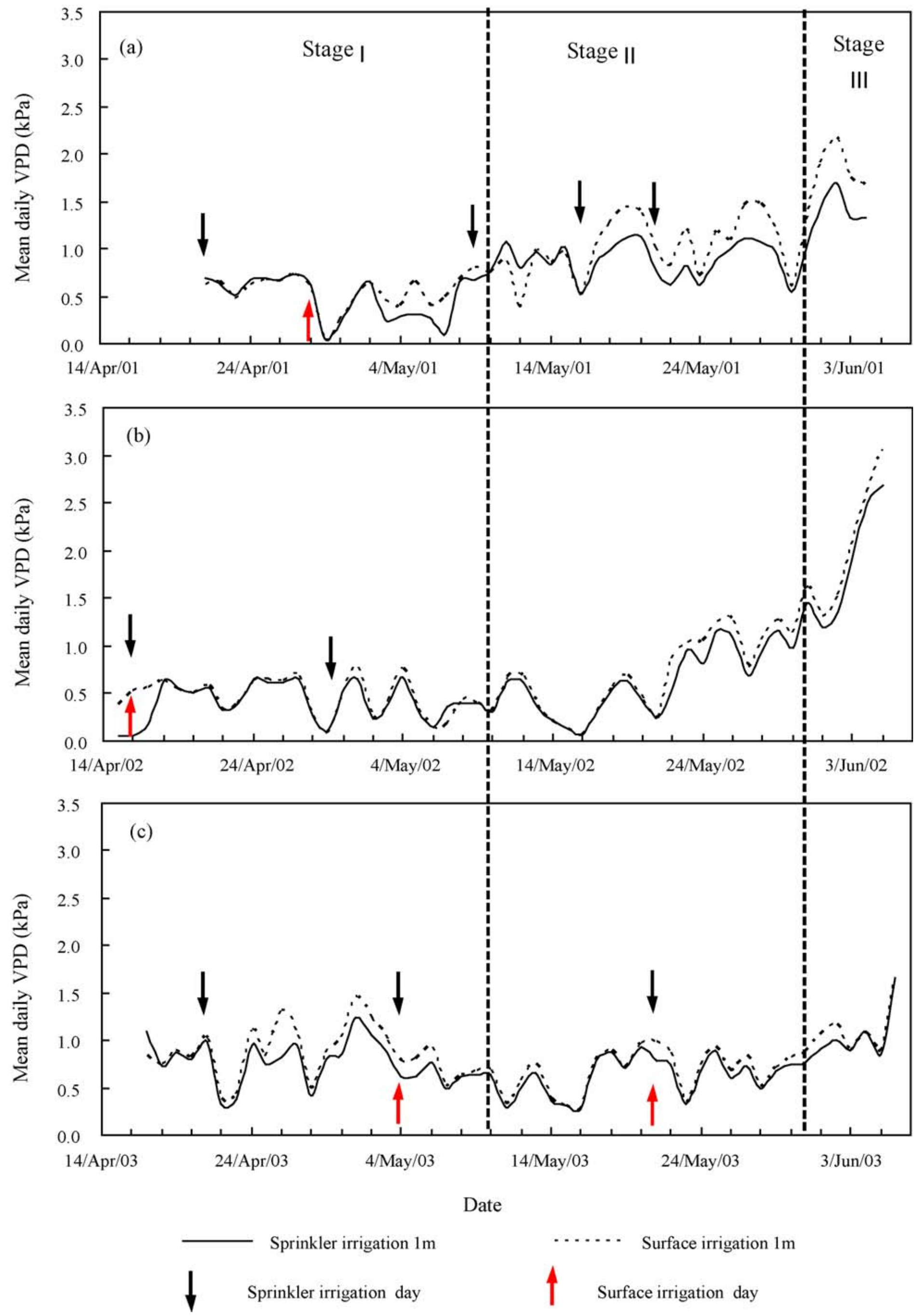

Fig. 8 – Daily average vapor pressure deficit (VPD, kPa) at 1 m height above ground surface in sprinkler and surface irrigated fields from April 14 to winter wheat harvest day in 2001 (a), 2002 (b) and 2003 (c).

the response of field air temperature to sprinkler irrigation at sprinkler irrigation intervals (Fig. 3 and Table 3). Mean reduction in value of VPD during daytime at sprinkler irrigation intervals was a function of time after sprinkler irrigation and climatic condition, and was regressed using data from May 4 to 30 in 2003 as follows:

$$\Delta\mathrm{VPD} = (-0.2365 + 0.02855T_{\mathrm{ave}} - 0.00279\mathrm{RH}_{\mathrm{ave}} + 0.1343U_{\mathrm{ave}})D^{-0.5222}, \quad R^2 = 0.69 \tag{5}$$

where D is the number of days after sprinkler irrigation. The value of D is 1 on the sprinkler irrigation day. ΔVPD is mean reduction in value of VPD at 1 m height over daytime on the Dth day in the sprinkler-irrigated field in comparison with the surface irrigated field at the sprinkler irrigation intervals when sprinkler and surface irrigations cease simultaneously, kPa; T_{ave}, $\mathrm{RH}_{\mathrm{ave}}$, U_{ave} are mean daily air temperature (°C), relative humidity (%) and wind speed (m/s) at 2 m height on the Dth day measured at meteorological stations, respectively.

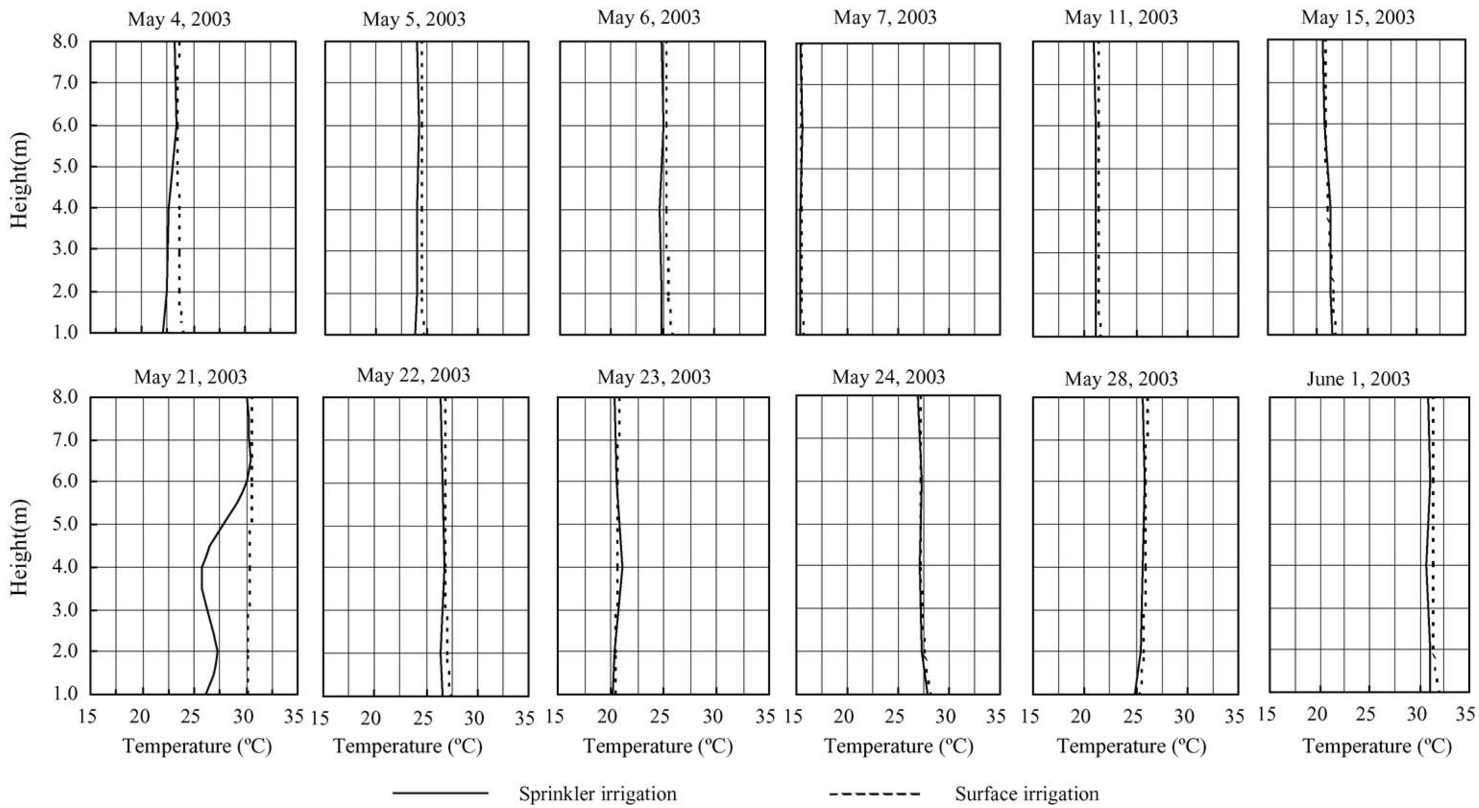

Fig. 9 – Vertical distribution of air temperature from 1 to 8 m height above ground surface measured at 14:00 h in sprinkler and surface irrigated fields at two sprinkler irrigation intervals in 2003, sprinkler irrigations and surface irrigations stopped at the same time on May 4 and 21, 2003.

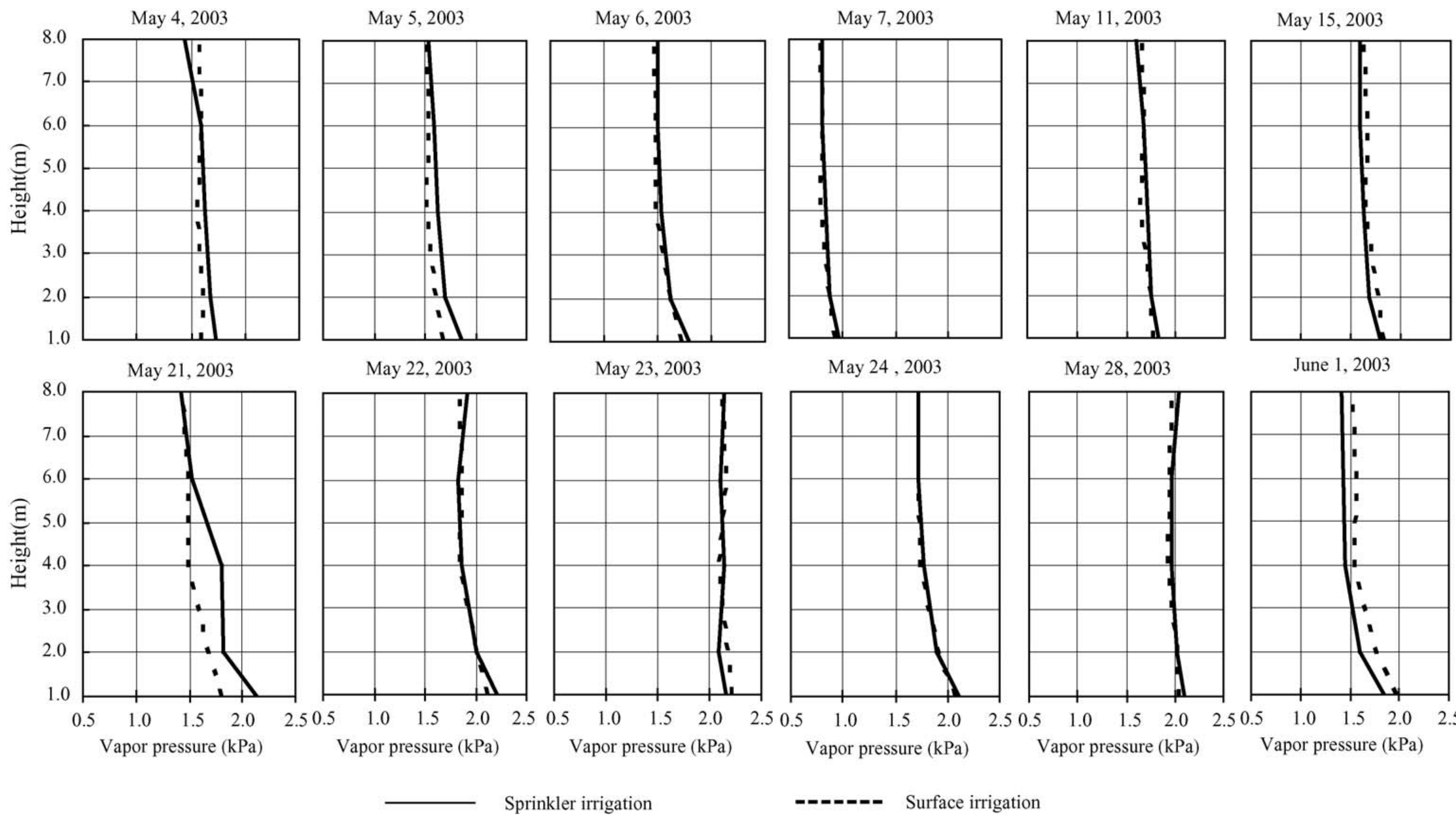

Fig. 10 – Vertical distribution of vapor pressure (kPa) from 1 to 8 m height above ground surface measured at 14:00 h in sprinkler and surface irrigated fields at two sprinkler irrigation intervals in 2003, sprinkler irrigations and surface irrigations stopped at the same time on May 4 and 21, 2003.

3.3. Effect of sprinkler irrigation on the maximum and mean daily air temperature and vapor pressure deficit

Air temperature at 14:00 h (generally as maximum daily temperature, T_{max}) at 1 m height was significantly smaller ($P < 0.001$) in the sprinkler-irrigated field than in the surface irrigated field throughout the three experimental seasons (Fig. 5 and Table 5). Mean daily air temperature (T_{ave}) in the sprinkler-irrigated field showed the same trend as T_{max} (Fig. 6 and Table 5). The T_{max} and T_{ave} at Stage I were significant reduced in 2003 by sprinkler irrigation respected to surface irrigation and those at Stages II and III in all of the three seasons. The reduced value of T_{max} and T_{ave} at Stage I in the sprinkler-irrigated field was not significant in 2001.

VPD at 14:00 h ($VPD_{14:00}$) and mean daily VPD (VPD_{ave}) at 1 m height were significantly smaller ($P < 0.001$) in the sprinkler-irrigated field than in the surface irrigated field throughout the experimental period in the three seasons (Figs. 7 and 8, Table 5). During the three seasons, $VPD_{14:00}$ and VPD_{ave} at Stage I were significantly reduced by sprinkler irrigation in 2003 in comparison with 2001 and 2002 and those at Stages II and III in 2001 and 2002 in comparison with 2003. The reduced value of VPD_{ave} in the sprinkler-irrigated field averaged over a whole season was highest in 2001, followed by 2002 and 2003 (Table 5).

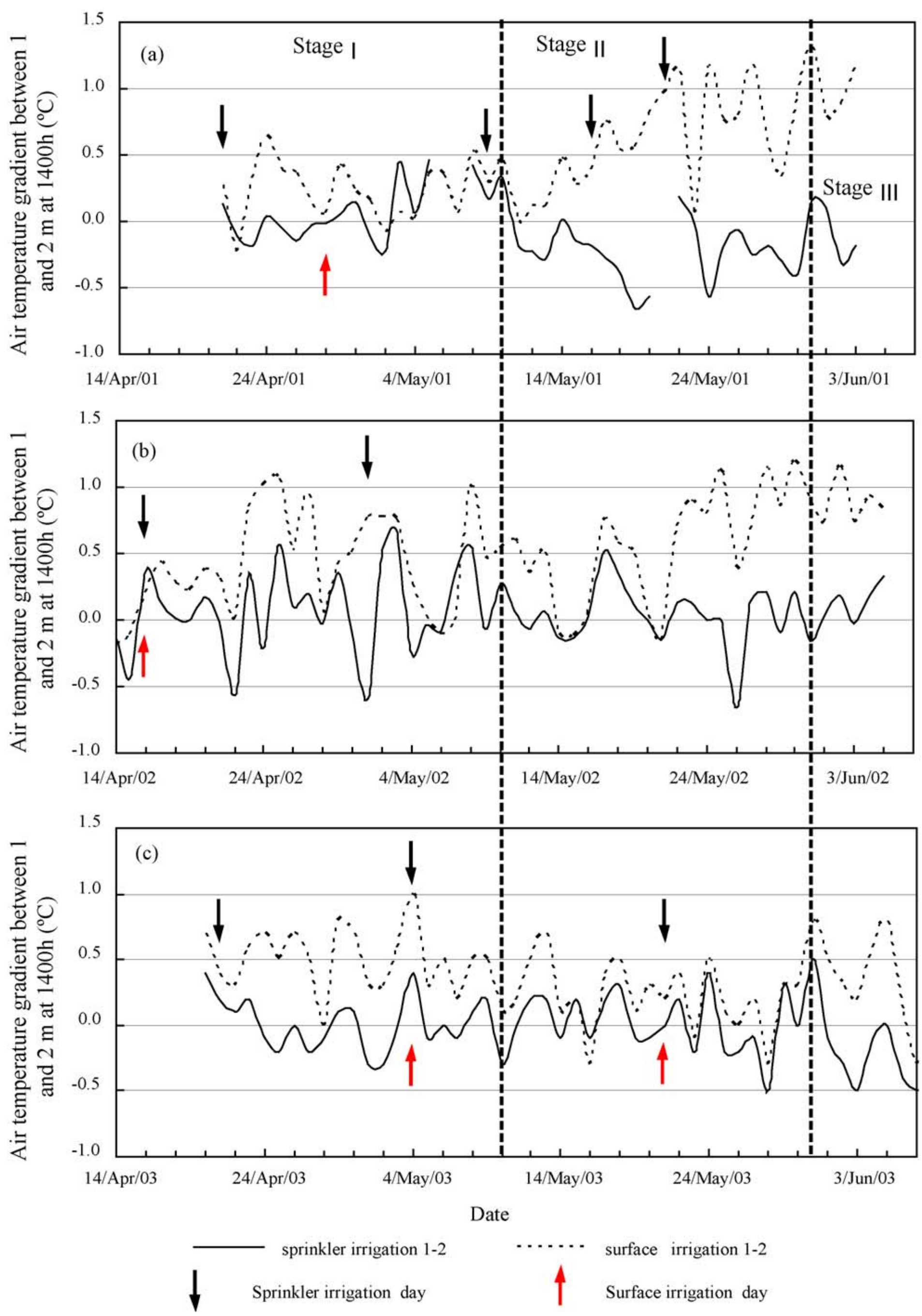

Fig. 11 – Gradient of air temperature from 1 to 2 m heights above ground surface measured at 14:00 h in sprinkler and surface irrigated fields from April 14 to winter wheat harvest days in 2001 (a), 2002 (b) and 2003 (c).

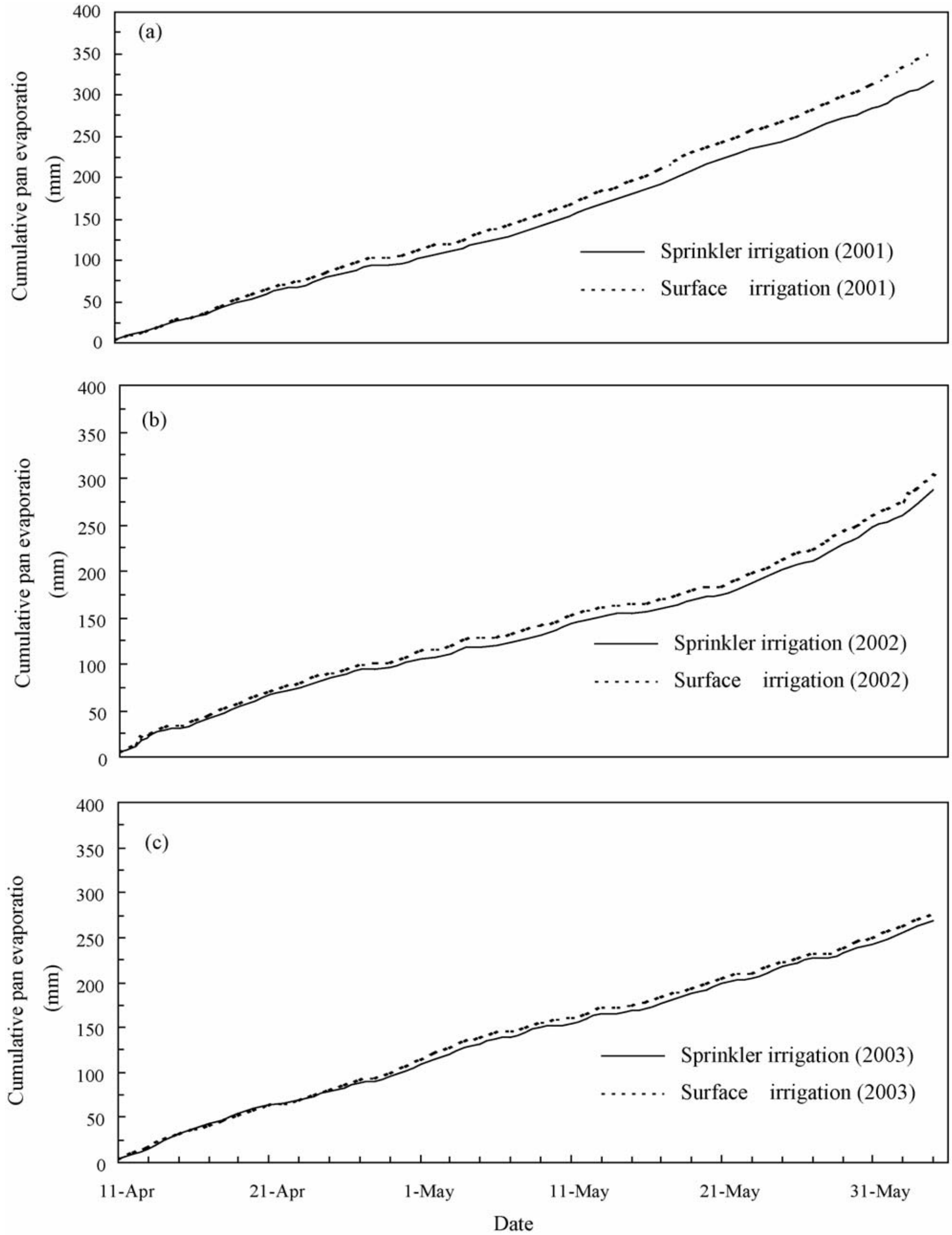

Fig. 12 – Cumulative water surface evaporation measured using standard 20 cm diameter pan placed on the top of canopy under sprinkler and surface irrigation conditions between April 11 and June 4 in 2001 (a), 2002 (b) and 2003 (c).

Air temperatures averaged over Stages II and III in the sprinkler-irrigated field were 2.1%, 1.7% and 2.0% lower than that in the surface irrigated field in the first, second and third seasons, respectively. While the daily VPD averaged over the corresponding stages in the sprinkler-irrigated field were 15.3%, 10.7% and 9.5% lower than in the surface irrigated fields in the first, second and third seasons, respectively. Table 3 showed that the effect of sprinkler irrigation on air temperature lasted for two and three days after irrigations, while the VPD, especially during daytime, was affected throughout sprinkler irrigation intervals (Table 4). It can be concluded that the effect of sprinkler irrigation on VPD not only lasted for a relatively longer time but also was stronger in comparison with on air temperature.

3.4. *Effect of sprinkler irrigation on vertical distributions of air temperature and vapor pressure*

Vertical distribution of air temperature at 14:00 h in the sprinkler and surface irrigated fields at two sprinkler irrigation intervals, from May 4 to 15 and from May 21 to 31 in 2003, was shown in Fig. 9. The air temperatures at heights from 1 to 8 m in the sprinkler-irrigated field were smaller than in the surface irrigated field except for those rainy days of May 6, 11, 23 and 28. The difference in air temperatures between in the sprinkler and surface irrigated fields decreased with the increase of time and height. Significant temperature inversion above canopy appeared during sprinkler irrigation days, which according to Tanny et al. (2003), stabilizes the air and reduces mixing;

therefore limiting vertical vapor exchanges. Vertical distributions of vapor pressures in the sprinkler-irrigated field were also different with in the surface irrigated field (Fig. 10). The vapor pressures, at heights 1–8 m, were larger in the sprinkler-irrigated field than in the surface irrigated field except for the rain days of May 6, 11, 23 and 28.

Gradient values of air temperature from 1 to 2 m heights at 14:00 h in the sprinkler-irrigated field were smaller than in the surface irrigated field in the three seasons (Fig. 11 and Table 5). While the gradient values in the sprinkler and surface irrigated fields were different at the three stages in the three seasons (Table 5). At Stage I, the gradient of air temperature was significantly reduced by sprinkler irrigation in 2002 and 2003 ($P < 0.05$), while no significant difference was found in 2001. At Stages II and III, significant reduction in air temperature gradient in the sprinkler-irrigated field respected to surface irrigated field was found in 2001 and 2002 ($P < 0.01$). Theoretically, larger air temperature gradient will result in more vapor exchange at the vertical direction. Based on the above results, the vapor transfer, therefore, will be smaller in the sprinkler-irrigated field in comparison with in the surface irrigated field.

3.5. *Effect of sprinkler irrigation on pan evaporation*

Pans evaporation provides an integrated index to quantify the effect of radiation, wind, temperature and humidity on the vapor exchange between the surface of open water and the air. From April 14 to June 4, the cumulative E_{pan} in the sprinkler-irrigated field was consistently smaller than in the surface irrigated field in all of the three seasons (Fig. 12 and Table 5). From April 11 to June 4, the cumulative E_{pan} was 354 and 316 mm for surface and sprinkler irrigations, respectively, in the first season, 304 and 288 mm in the second season, and 277 and 269 mm in the third season. The values of cumulative E_{pan} were 11%, 5% and 3% lower in the sprinkler-irrigated field than in the surface irrigated field in the first, second and third seasons, respectively. The difference in E_{pan} between in the sprinkler and surface irrigated fields during 2001 and 2002 were significant ($P < 0.01$), excluding 2003 (Table 5).

4. Discussion

Reduced air temperature, VPD and pan evaporation in the sprinkler-irrigated field in comparison with in the surface irrigated field (Figs. 3–12, Tables 3–5) are related to not only the number of irrigation events but also climatic conditions. There were five, two and four sprinkler irrigation events in comparison with one, one and two surface irrigations between April and May in the first, second and third seasons (Table 1), respectively. More events of sprinkler irrigation in comparison with surface irrigation events could enhance and prolong a lower air temperature and VPD in the sprinkler-irrigated field because sprinkler irrigation significantly affects air temperature and VPD at sprinkler irrigation intervals (Tables 3 and 4).

Date in meteorological station (Fig. 2 and Table 2) showed that, at Stage I, air temperature was significantly higher, relative humidity was significantly lower in 2003 in comparison to 2001; conversely, at Stage II, air temperature was significantly higher and relative humidity was lower in 2001 in comparison to 2003. In comparison to surface irrigation, sprinkler irrigation significantly ($P < 0.001$) affected field air temperature, VPD and temperature gradient at Stage I in 2003 and those at Stage II in 2001 (Table 5). The higher air temperature and the lower humidity, the greater reduction in values of air temperature, VPD and air temperature gradient in the sprinkler-irrigated field in comparison to surface irrigated field.

Mean wind speed at Stage I was 1.5 m/s, and significantly higher than that of 0.9 m/s at Stages II and III in 2003 (Table 2). Mean daily air temperature, VPD and air temperature gradient at Stage I in 2003 were significantly ($P < 0.001$) influenced in the sprinkler-irrigated field (Table 5). While these variables at Stage II in 2003, except for air temperature, were not significantly affected by sprinkler irrigation. The reduction in values of air temperature, VPD and temperature gradient in the sprinkler-irrigated field changed consistently with wind speed. The higher the wind speed, the greater reduction in air temperature, VPD and temperature gradient occurred in the sprinkler-irrigated field respected to surface irrigated field. These relationships between reduced values of air temperature and VPD in the sprinkler-irrigated field with wind speed can also be seen from Eqs. (4) and (5). Therefore, wind speed is one of major factors that influence the affect of sprinkler irrigation on field microclimate.

All of the three experimental seasons consists of three stages that are winter wheat developing stage, middle stage and late stage, which is similar to Stages I–III. Plant height increased with time in the developing stage and kept constant when the maximum value reaches in the middle and late season. Crop leaf area index (LAI) also increased with time in the developing stage, kept a relative constant value in the middle stage and dropped down quickly in the late season. Field microclimate at Stage I in 2003 was significantly affected by sprinkler irrigation respected to 2002 and 2003 while those at Stage II in 2001 respected to 2003 (Table 5). The effect of sprinkler irrigation on air temperature, VPD and temperature gradient did not follow the same way as plant height and LAI change during three experimental seasons. It shows that plant growth is not a major factor that influences the effect of sprinkler irrigation on field microclimate at the present experiment.

5. Conclusions

Field microclimate was significantly affected by sprinkler irrigation not only during the period of irrigation but also during all irrigation intervals. Within daytime, air temperature and VPD above winter wheat canopy were smaller in the sprinkler-irrigated field than in the surface irrigated field. The effect of sprinkler irrigation on VPD lasted throughout sprinkler irrigation intervals, while the effect on air temperature only lasted 2–3 days after irrigation. Temperature gradient from 1 to 2 m was smaller in the sprinkler-irrigated field than in the surface irrigated field. The cumulative E_{pan} measured by using standard 20 cm diameter pan was smaller in the sprinkler-irrigated field in comparison with in the surface irrigated field from winter wheat elongation stage to maturation stage. The smaller E_{pan} in the sprinkler-irrigated field indicated that air temperature, VPD and temperature gradient were smaller in the sprinkler-irrigated field in comparison with in the surface irrigated field. Effects of sprinkler irrigation on field microclimate showed to be more significant under the climatic conditions with relatively higher air temperature, lower VPD, less and non-uniformly distributed rainfall and higher wind speed.

Acknowledgements

The authors gratefully acknowledge Prof. Guanhua Huang for helpful suggestions during the course of the study, Daniel Elmowitz for English language help and two anonymous reviewers for their helpful comments. This study is the part work of Project 40125002 supported by the National Science Fund for Distinguished Young Scholars and Project 50509025 supported by National Natural Science Foundation of China.

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56. United Nations Food and Agriculture Organization, Rome.

Ayars, J.E., Hutmacher, R.B., Schoneman, R.A., Dettinger, D.R., 1991. Influence of cotton canopy on sprinkler irrigation uniformity. Trans. ASAE 34, 890–896.

Chen, J.Y., Tang, C.Y., Shen, Y.J., Sakura, Y., Kondoh, A., Shimada, J., 2003. Use of water balance calculation and tritium to examine the dropdown of groundwater table in the piedmont of the North China Plain (NCP). Environ. Geol. 44, 564–571.

Chen, Z., 1996. Analysis on agro-meteorological effect on mulberry field under sprinkler irrigation condition. J. Hangzhou Univ. (Nat. Sci. Div.) 23 (1), 92–99.

Dylla, A.S., Shull, H., 1983. Estimating losses from a rotating-boom sprinkler. Trans. ASAE 26, 123–125.

Frost, K.R., Schwalen, H.C., 1955. Sprinkler evaporation losses. Agric. Eng. 36, 526–528.

Kang, Y., Wang, F.X., Liu, H.J., Yuan, B.Z., 2004. Potato evapotranspiration and yield under different drip irrigation regimes. Irrig. Sci. 23, 133–143.

Kohl, K.D., Kohl, R.A., Deboer, D.W., 1987. Measurement of low pressure sprinkler evaporation loss. Trans. ASAE 30, 1071–1074.

Kohl, R.A., Wright, J.L., 1974. Air temperature and vapor pressure changes caused by sprinkler irrigation. Agron. J. 66, 85–87.

Li, J., Rao, M., 2000. Sprinkler water distributions as affected by winter wheat canopy. Irrig. Sci. 20, 29–35.

Li, J., Rao, M., 2003. Field evaluation of crop yield as affected by nonuniformity of sprinkler-applied water and fertilizers. Agric. Water Manage. 59, 1–13.

Liu, C., Zhang, X., Zhang, Y., 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agric. For. Meteorol. 111, 109–120.

Liu, H.J., Kang, Y., Liu, W., 2004. Regulating field microclimate using sprinkler irrigation under dry-hot wind condition. In: Huang, G.H., Pereira, L.S. (Eds.), Land and Water Management, Proceedings of the Seventh Inter Regional Conference on Environment and Water, vol. I. China Agriculture Press, China, pp. 386–393.

Liu, X., Ju, X., Zhang, F., Pan, J., Christie, P., 2003. Nitrogen dynamics and budgets in a winter wheat–maize cropping system in the North China Plain. Field Crops Res. 83, 111–124.

Mao, X., Liu, M., Wang, X., Liu, C., Hou, Z., Shi, J., 2003. Effects of deficit irrigation on yield and water use of greenhouse grown cucumber in the North China Plain. Agric. Water Manage. 61, 219–228.

Norman, J.M., Campbell, G., 1983. Application of plant environment model to problems in irrigation. In: Hillel, D. (Ed.), Advance in Irrigation, vol. 2. Academic Press, New York, pp. 155–188.

Steiner, J.L., Kanemasu, E.T., Clark, R.N., 1983. Spray losses and partitioning of water under a center pivot sprinkler system. Trans. ASAE 20, 1128–1134.

Sun, Z., Kang, Y., Liu, H.J., 2004. Studies on soil water and nitrate distribution under sprinkler irrigation condition. In: Huang, G.H., Pereira, L.S. (Eds.), Land and Water Management, Proceedings of the Seventh Inter Regional Conference on Environment and Water, vol. II. China Agriculture Press, China, pp. 1289–1295.

Tanny, J., Cohen, S., Teitel, M., 2003. Screenhouse microclimate and ventilation: an experimental study. Biosyst. Eng. 84 (3), 331–341.

Tarjuelo, J.M., Ortega, J.F., Montero, J., DeJuar, J.A., 2000. Modeling evaporation and drift losses in irrigation with medium size impact sprinklers under semi-arid conditions. Agric. Water Manage. 43, 263–284.

Thompson, A.L., Gilley, J.R., Norman, J.M., 1993a. A sprinkler water droplet evaporation and plant canopy model: I. Model development. Trans. ASAE 36, 735–741.

Thompson, A.L., Gilley, J.R., Norman, J.M., 1993b. A sprinkler water droplet evaporation and plant canopy model: II. Model application. Trans. ASAE 36, 743–750.

Thompson, A.L., Martine, D.L., Norman, J.M., Tolk, J.A., Howell, T.A., Gilley, J.R., Schneider, A.D., 1997. Testing of a water loss distribution model for moving sprinkler system. Trans. ASAE 40, 81–88.

Tolk, J.A., Howell, T.A., Steiner, J.L., Krieg, D.R., 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. Irrig. Sci. 16, 89–95.

Walter, L.T., 1988. Sprinkler evaporation loss equation. J. Irrig. Drain. Eng. ASCE 113, 616–620.

Wang, F., Wang, X., Ken, S., 2004. Comparison of conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. Field Crops Res. 87, 35–42.

Wang, H., Zhang, L., Dawes, W.R., Liu, C., 2001. Improving water use efficiency of irrigated crops in the North China Plain—measurements and modeling. Agric. Water Manage. 48, 151–167.

Washington, L.C.S., Larry, G.J., 1988a. Modeling evaporation and microclimate changes in sprinkler irrigation: 1. Model formulation and calibration. Trans. ASAE 31, 1481–1486.

Washington, L.C.S., Larry, G.J., 1988b. Modeling evaporation and microclimate changes in sprinkler irrigation: 2. Model assessment and application. Trans. ASAE 31, 1487–1493.

Yang, X., Chen, F., Gong, F., Song, D., 2000. Physiological and ecological characteristics of winter wheat under sprinkler irrigation condition. Trans. Chin. Soc. Agric. Eng. 16 (3), 35–37.

Yuan, B., Kang, Y., Nishiyama, S., 2001. Drip irrigation scheduling for tomatoes in unheated greenhouses. Irrig. Sci. 20, 149–154.

Zhang, X., Pei, D., Hu, C., 2003. Conserving groundwater for irrigation in the North China Plain. Irrig. Sci. 21, 159–166.

Zhang, Y., Kendy, E., Yu, Q., Liu, C., Shen, Y., Sun, H., 2004. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. Agric. Water Manage. 64, 107–122.