

2009

Crop coefficients for cotton in northeastern Louisiana

Sean Allen Hribal

Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses



Part of the [Social and Behavioral Sciences Commons](#)

Recommended Citation

Hribal, Sean Allen, "Crop coefficients for cotton in northeastern Louisiana" (2009). *LSU Master's Theses*. 3257.
https://digitalcommons.lsu.edu/gradschool_theses/3257

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master's Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.

CROP COEFFICIENTS FOR COTTON IN NORTHEASTERN LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geography and Anthropology

by
Sean Allen Hribal
B.S., California University of Pennsylvania, 2006
August, 2009

ACKNOWLEDGMENTS

I would like to thank Dr. Ernest Clawson for his guidance in the agricultural aspects of this project and his support during my presentations. I have become a more well-rounded scholar because of his efforts. I thank Dr. Robert Rohli for instructing me in the climatological-side of this project and his diligence in editing my thesis. My gratitude goes to Dr. David Brown for his insights into synoptic climatology and climate change. I am grateful to Dr. Barry Keim for adding extreme event analysis to my climatological “toolbox.” I would like to thank my undergraduate advisor Dr. Chad Kauffman who informed me of the graduate assistantship at LSU.

I am grateful for everyone at the LSU AgCenter Northeast Research Station who helped me with my fieldwork and housing. I am also grateful to Cotton Inc. for funding this project.

As always, I am thankful for the support of my parents Jon and Marsha Hribal. I also thank Patti Newell who is a great source of encouragement and inspiration.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	ii
LIST OF TABLES	iv
LIST OF FIGURES	v
ABSTRACT.....	vii
CHAPTER 1. OVERVIEW	1
CHAPTER 2. BACKGROUND AND LITERATURE REVIEW	6
2.1 Crop Evapotranspiration.....	6
2.2 Reference Evapotranspiration.....	7
2.3 Crop Coefficients.....	9
2.4 Irrigation Scheduling	13
CHAPTER 3. DATA AND METHODS	15
3.1 Lysimeter Site and Design.....	15
3.2 Lysimeter Calibration	17
3.3 Lysimeter Measurements.....	18
3.4 Tensiometer Measurements.....	20
3.5 Weather Measurements and the Standardized Reference Evapotranspiration Equation.....	22
3.6 Cotton Establishment, Management, and Measurement	26
CHAPTER 4. RESULTS AND DISCUSSION.....	31
4.1 Crop Evapotranspiration.....	31
4.2 Precipitation.....	33
4.3 Reference Evapotranspiration.....	36
4.4 Crop Coefficients.....	44
CHAPTER 5. CONCLUSIONS	52
5.1 Review	52
5.2 Results.....	52
5.3 Real-World Application.....	54
REFERENCES	56
VITA.....	60

LIST OF TABLES

Table 1.1 Departure from normal monthly temperature (DPNT) ($^{\circ}\text{C}$) and departure from normal monthly precipitation (DPNP) (mm) at the NOAA COOP weather station St. Joseph 3 N for 2007 from National Climatic Data Center (NCDC) monthly surface data.....	4
Table 4.1 Stage averaged K_c values and linear regression values of y-intercept (a_0), slope (a_1), coefficient of determination (R^2), and standard error (s_{yx}) for predicting K_c values ((N) denotes north lysimeter, (S) south lysimeter, and (NA) unavailable results)	46

LIST OF FIGURES

Figure 1.1 Map of Louisiana identifying Franklin, Morehouse, and Tensas Parishes	1
Figure 1.2 Climograph of monthly normals (1971-2000) of mean surface air temperature (points) and total precipitation (bars) from the NOAA COOP station St. Joseph 3 N	3
Figure 1.3 Climograph of 2007 monthly mean surface air temperature (points) and total precipitation (bars) from the NOAA COOP station St. Joseph 3 N	3
Figure 3.1 Lysimeter field site at the Northeast Research Station with (a) denoting cotton fields, (b) rice fields, and a star marking the location of the lysimeters (prevailing winds are southerly) (Clawson <i>et al.</i> , 2009).....	15
Figure 3.2 Weighing lysimeters with developing cotton crop (Clawson <i>et al.</i> , 2009)	16
Figure 3.3 Cross-section diagram of weighing lysimeter (Clawson <i>et al.</i> , 2009)	16
Figure 3.4 Typical K_c curve (Allen <i>et al.</i> , 1998)	30
Figure 4.1 North lysimeter mass for 2007 with (I) denoting irrigation, (R) rainfall, and (P) pumping	31
Figure 4.2 South lysimeter mass for 2007 with (I) denoting irrigation, (R) rainfall, and (P) pumping	32
Figure 4.3 North lysimeter mass measurements on 11 August 2007	33
Figure 4.4 Precipitation measured using the Louisiana Agriclimatic Information System (LAIS) weather station at the Northeast Research Station in 2007.....	34
Figure 4.5 ET_c at the Northeast Research Station in 2007.....	35
Figure 4.6 Total solar radiation in 2007.....	37
Figure 4.7 Surface temperature in 2007.....	38
Figure 4.8 Average wind speed at 2 m in 2007	39
Figure 4.9 Relative humidity in 2007	40
Figure 4.10 ET_o at the Northeast Research Station in 2007	41
Figure 4.11 ET_o comparison plots	42
Figure 4.12 Monthly E^o calculated using the adjusted Thornthwaite method and monthly ET_o using the SREE	43

Figure 4.13 K_c values.....	44
Figure 4.14 K_c values, trendlines, and growth stages (emergence (EM), pin-head square (PHS), match-head square (MHS), and first flower (FF)).....	45
Figure 4.15 K_c as a percentage of its maximum value (1.98 for north lysimeter and 1.58 for south lysimeter) versus plant height as a percentage of its maximum value (152.6 cm for the north lysimeter and 142.6 cm for the south lysimeter).....	47
Figure 4.16 K_c as a percentage of its maximum value versus main stem nodes as a percentage of its maximum value (28.0 for the north lysimeter and 23.8 for the south lysimeter)	48
Figure 4.17 K_c as a percentage of its maximum value versus internode length as a percentage of its maximum value (3.7 cm for the north lysimeter and 3.8 cm for the south lysimeter).....	49
Figure 4.18 K_c versus NAWF	50
Figure 4.19 Crop canopy photographs at 25, 50, and 80 percent coverage (from top to bottom)	51

ABSTRACT

Daily crop coefficients (K_c) were determined for irrigated cotton (*Gossypium hirsutum* L.) at the Louisiana State University (LSU) AgCenter Northeast Research Station near St. Joseph, Louisiana, in 2007. K_c values were calculated using daily crop evapotranspiration (ET_c), which was measured using paired weighing lysimeters, and daily reference evapotranspiration (ET_o), which was calculated using the Standardized Reference Evapotranspiration Equation (SREE) for a short crop. Meteorological data for input into the SREE were obtained from a nearby Louisiana Agrilclimatic Information System (LAIS) weather station and an on-site portable weather station.

Averaged K_c values were 0.15, 0.64, and 1.39 for the initial (day 22 to 29), development (day 30 to 69), and mid-season (day 70 to 136) stages. The beginning of the mid-season stage corresponded closely with first flower (FF), maximum internode length, and 80 percent crop canopy cover. Also, the relationship between K_c and day after planting was determined for each stage. K_c values from this study can be used to estimate ET_c for irrigated cotton in a clay soil in northeastern Louisiana.

CHAPTER 1. OVERVIEW

In many regions of the southern United States, the absence or deficiency of irrigation can harm plant health and decrease yield. On the other hand, excessive irrigation wastes water and accelerates soil erosion (Soil Conservation Service, 1982). Conservation irrigation maximizes yield while minimizing runoff and requires accurate estimates of crop evapotranspiration (ET_c) (Soil Conservation Service, 1982).

Northeastern Louisiana relies on irrigation for cotton production. The United States Department of Agriculture – National Agricultural Statistics Service (USDA-NASS) Census of Agriculture (2002) reported the following facts regarding Louisiana cotton production. In 2002, irrigated cotton acreage comprised 32 percent of the total cotton acreage, and irrigated cotton farms comprised 43 percent of all cotton farms in Louisiana – a state which ranked eighth in harvested upland cotton with 737,641 bales. Tensas Parish, located in northeastern Louisiana (Figure 1.1), was the most productive cotton-producing parish in the state in harvested acreage

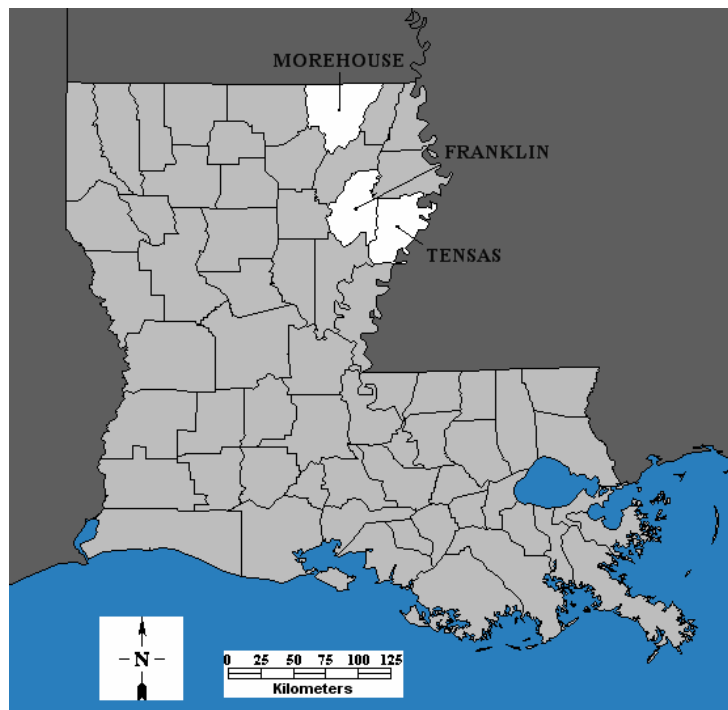


Figure 1.1 Map of Louisiana identifying Franklin, Morehouse, and Tensas Parishes

and bales. For that parish, irrigated cotton acreage comprised 12 percent of the total cotton acreage, and irrigated cotton farms comprised 32 percent of all cotton farms. Other top producing parishes in Louisiana such as Morehouse and Franklin are also located in the northeast region, and over 60 percent of their cotton acreage was irrigated in 2002.

Despite high rainfall totals in Louisiana, the months of June, July, and August typically experience conditions where, for most crops, ET_c exceeds precipitation (Soil Conservation Service, 1982). This period also coincides with cotton growth stages from squaring to boll maturation, during which time cotton ET_c is high (Tharp, 1960). Cotton consumes approximately 562 kg of water per kg of total plant material (Tharp, 1960).

To determine the climatological “fingerprint” at the study site, the Northeast Research Station in Tensas Parish, a normals climograph (1971 to 2000) (Figure 1.2) and a climograph of 2007 observations (Figure 1.3) were constructed. The National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Network (COOP) station St. Joseph 3 N was selected because of its long, continuous record of observations and its close proximity to the Louisiana Agriculimatic Information System (LAIS) weather station at the Northeast Research Station (the stations are located a few meters apart).

The normals climograph shows lower precipitation in the warm season and higher precipitation in the cool season, with a monthly minimum of 77.7 mm in September and maxima of 160.3 mm in January and March (Figure 1.2). Temperature varies from a minimum of 8.0°C in January to a maximum temperature of 28.2°C in July. According to the normals climograph, the climate at the Northeast Research Station can be classified as humid subtropical (Cfa) using the Köppen climate classification system. The 2007 climograph shows an uneven pattern of precipitation with a monthly maximum of 408.7 mm in July and a monthly minimum of 13.5 mm

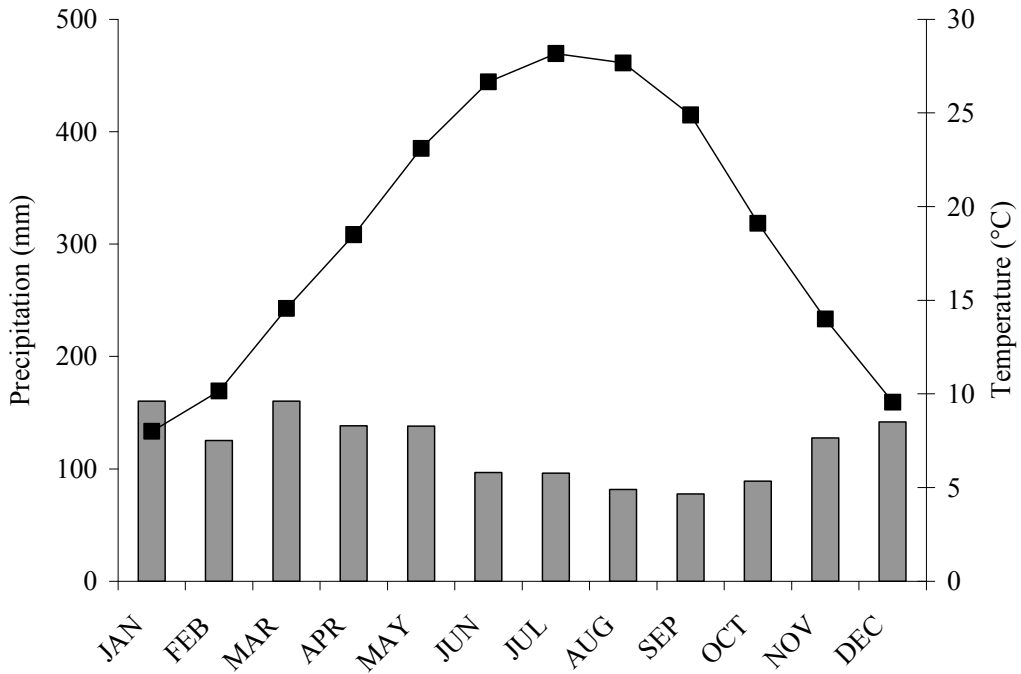


Figure 1.2 Climograph of monthly normals (1971-2000) of mean surface air temperature (points) and total precipitation (bars) from the NOAA COOP station St. Joseph 3 N

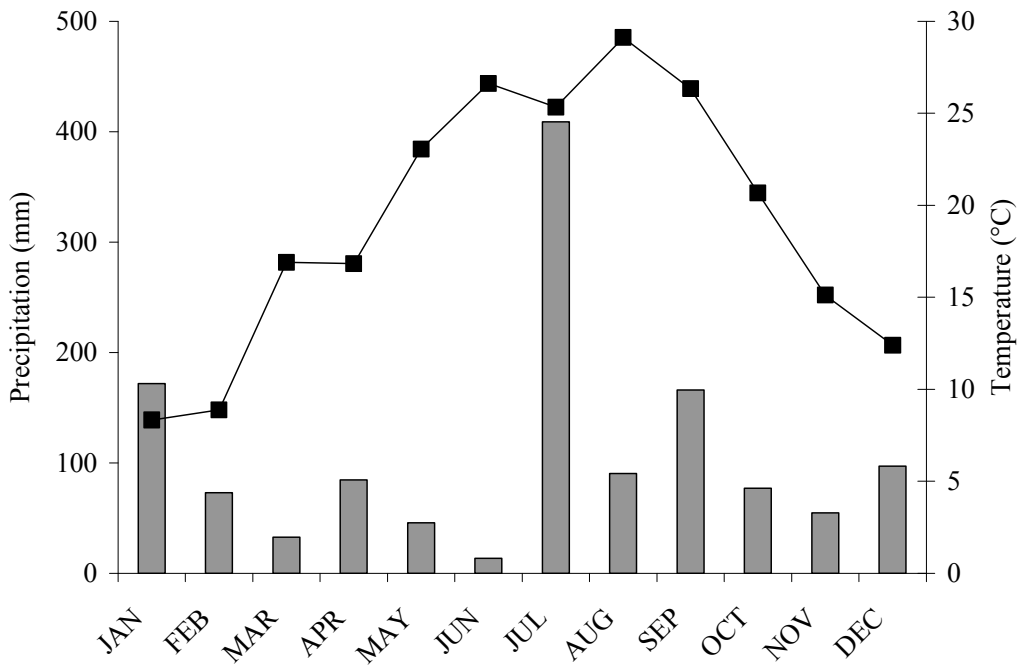


Figure 1.3 Climograph of 2007 monthly mean surface air temperature (points) and total precipitation (bars) from the NOAA COOP station St. Joseph 3 N

in June. The temperature curve for 2007 begins at 8.3°C in January, increases to 29.1°C in August, and decreases to 12.4°C in December.

The 2007 cotton growing season at the Northeast Research Station extended from May to September. For May and June 2007, the mean monthly temperature was near normal (Table 1.1). The mean monthly temperature was almost 3°C higher than normal for July and 1.4°C higher for August and September. For May and June 2007, the mean monthly precipitation was lower than normal by 92.5 and 83.3 mm, respectively. The mean monthly precipitation was far higher than normal for July by 312.4 mm. The mean monthly precipitation for August was near normal, but the mean monthly precipitation for September was 88.4 mm higher than normal.

Table 1.1 Departure from normal monthly temperature (DPNT) (°C) and departure from normal monthly precipitation (DPNP) (mm) at the NOAA COOP weather station St. Joseph 3 N for 2007 from National Climatic Data Center (NCDC) monthly surface data

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
DPNT	0.3	-1.3	2.3	-1.7	-0.1	-0.1	-2.8	1.4	1.4	1.6	1.1	2.8
DPNP	11.4	-52.3	-127.5	-53.9	-92.5	-83.3	312.4	8.4	88.4	-11.9	-72.9	-44.7

Evapotranspiration (ET) is the combined term for evaporation and transpiration (Brady, 1990). Evaporation is the change of state of water from liquid to gas. Transpiration is the diffusion of water vapor from the stomata of plant leaves to the atmosphere (Taiz and Zeiger, 1998). ET_c includes evaporation from a soil surface and transpiration from a uniform crop. Crop coefficients (K_c) are calculated as

$$K_c = ET_c / ET_o$$

where ET_o represents reference evapotranspiration, which is evapotranspiration from a well-watered grass surface. Considering that K_c values are important for conservation irrigation scheduling and that conservation irrigation scheduling benefits farms in northeastern Louisiana, this research addresses the question:

- What are K_c values for cotton in northeastern Louisiana?

The answer requires the measurement of ET_c and the estimation of ET_o over an experimental period. The former was measured using paired weighing lysimeters. The latter was estimated using the Standardized Reference Evapotranspiration Equation (SREE) (Allen *et al.*, 2005) with the input of meteorological data from an LAIS weather station and a portable weather station. Cotton growth stages were marked along the K_c curve to provide a reference for farmers. Field research was conducted during the 2007 growing season at the LSU AgCenter Northeast Research Station located in Tensas Parish.

This project provides K_c values from which cotton ET_c can be estimated more accurately compared to other methods such as “feel and appearance” or pan evaporation (Soil Conservation Service, 1982). The “feel and appearance” method estimates available water capacity; however, it does not provide quantitative rates of soil water evaporation. This method is limited in accuracy because it relies on subjective judgments of soil properties. Pan evaporation lacks in accuracy for estimating ET_c because it does not account for crop characteristics such as stomatal behavior and surface roughness. Thus, use of K_c will improve the farmers’ knowledge of how frequently and how much to irrigate. Similar studies using lysimeters have been conducted and are ongoing in the southern United States, particularly in Georgia, Texas, and Arizona (Hunsaker, 1999; Howell *et al.*, 2004; Suleiman *et al.*, 2007). The study area was selected because of the importance of cotton in the surrounding region and the availability of reliable lysimetric data at the Northeast Research Station.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

2.1 Crop Evapotranspiration

Because all weather and climate is driven by solar radiant energy and the imbalance of energy receipt across the earth-ocean-atmosphere system, to understand the properties of evapotranspiration properly it is first necessary to review the atmospheric radiation balance:

$$Q^* = (K \downarrow - K \uparrow) + (L \downarrow - L \uparrow)$$

where Q^* represents net radiant energy, $K \downarrow$ is shortwave (*i.e.*, solar) energy emitted by the atmosphere to the surface, $K \uparrow$ represents the shortwave energy flux from the surface to the atmosphere, $L \downarrow$ is longwave (*i.e.*, terrestrial) energy emitted by the atmosphere to the surface, and $L \uparrow$ represents longwave energy going from the surface to the atmosphere. Once radiant energy reaches the surface, convection and conduction transfer energy within the earth-ocean-atmosphere system. Specifically,

$$Q^* = Q_H + Q_E + Q_G$$

where Q_H represents the convective flux of sensible heat (defined as positive in the “up” direction), Q_E is the convective flux of latent heat (also defined as positive in the “up” direction), and Q_G represents the conductive flux of energy into the surface (substrate heat flux – defined as positive in the “down” direction). At local scales, this transfer is generally vertical, because gradients of energy (along with matter and momentum) are usually much greater in the vertical direction than horizontally. Meteorologists and climatologists must understand the processes governing the first two terms on the right side of the above equation particularly well because the two convective fluxes operate between the surface and the atmosphere. Evaporation is represented by Q_E above, and its magnitude affects and is affected by other terms in the equation. Q_E can be determined by multiplying the latent heat of vaporization by the evaporation rate.

ET_c is influenced by air temperature, humidity, solar radiation, and wind speed (Allen *et al.*, 2005); crop characteristics including canopy cover, stomatal resistance, and length of growing season (Hall, 2001); and soil characteristics (Burt *et al.*, 2005). Regarding canopy cover, energy exchange with the atmosphere increases as leaf area increases until the canopy closes. Although soil water evaporation dominates when crops are small, mature crops that obscure the soil surface increase total water loss due to transpiration from larger leaf surfaces (Hanks, 1992). In other words, transpiration slowly supplants evaporation as ET_c increases. Soil water availability encourages plant growth and subsequent increases in ET_o . However, deficient soil water can induce plant wilting or death (Brady, 1990). Units of ET_c are expressed as water depth per unit time to assure compatibility with hydrologic budget calculations (Hall, 2001). ET_c can be measured directly using lysimeters or estimated using the following equation (Burt *et al.*, 2005):

$$ET_c = K_c ET_o$$

2.2 Reference Evapotranspiration

In 1948, the concept of ET_o , then called potential evapotranspiration (PE), was first described in publications. The physicist H. L. Penman derived an equation for PE from mass transport and energy balance equations. He used this equation to estimate the ET from open water, bare soil, and turf (grass) at a point-location (Penman, 1948) and laid the foundation for modern ET_o equations. By contrast, C.W. Thornthwaite (1948) approached the subject from a geographical angle. He defined PE as “the transfer [of water to the atmosphere] that would be possible under ideal conditions of soil moisture and vegetation.” By this definition, ideal conditions occur when enough soil water is available to maximize ET. Thornthwaite developed an empirical PE equation and constructed a climatology of PE for the U.S. (Thornthwaite, 1948). An adjusted form of this equation is expressed as

$$E^o \text{ (mm month}^{-1}\text{)} = 0, T < 0^\circ\text{C}$$

$$E^o \text{ (mm month}^{-1}\text{)} = 16(10T/I)^a, 0^\circ\text{C} \leq T < 26.5^\circ\text{C}$$

$$I = \sum_1^{12} (T/5)^{1.514}$$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49$$

$$E^o \text{ (mm month}^{-1}\text{)} = -415.85 + 32.24T - 0.43T^2, T \geq 26.5^\circ\text{C}$$

$$E^o \text{ (mm month}^{-1}\text{)} = E^o [(\theta/30)(h/12)]$$

where T is mean monthly temperature ($^\circ\text{C}$), θ is length of month (days), and h is length of daylight (hours) on the fifteenth day of the month (Willmott *et al.*, 1985).

Current definitions of ET_o do not differ substantially from Thornthwaite's definition except in the specification of the vegetative characteristics of the reference surface. Allen *et al.* (2005) defined ET_o as, "the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation." The recommended vegetation is a short crop such as clipped grass or tall crop such as alfalfa (Allen *et al.*, 2005).

ET_o depends on several factors. Fetch – the distance from the point of measurement to the nearest upwind discontinuity – should extend an adequate length to maintain the integrity of atmospheric measurements because obstructions and surface irregularities can cause irregularities in the atmospheric profile (American Meteorological Society, 2007). Definitions of adequate fetch for a meteorological site vary between sources from fixed distances ranging from 20-200 m to relative distances from four to ten times the distance of the height of the nearest obstruction (EPA, 1990; Kirkham, 2005; Newkirk, 2006). Allen *et al.* (2005) suggested at least 100 m of fetch for weather stations used for determining ET_o .

Temporal variation in ET_o occurs mainly because of variation in solar radiation. Plant stomata open and close in response to the diurnal cycle of solar radiation, which increases and decreases transpiration, respectively. This is due to differences in water flow resistance caused by changes in stomatal aperture under different solar radiant intensities. The diurnal cycle of temperature, humidity, and wind speed also influences the temporal variation in ET_o . In northeastern Louisiana it is generally the case that higher temperature, lower humidity, and higher wind speed occur during the afternoon hours and contribute to increasing ET_o during this time of the day.

2.3 Crop Coefficients

A few general statements can be made on the behavior of K_c . In the initial stage, evaporation exceeds transpiration but K_c is low because soil water evaporation, which occurs from a shallow surface layer, is limited (Hall, 2001). At the development stage, K_c increases linearly as plant growth increases (Allen *et al.*, 1998). During mid-season, canopy closure limits soil water evapotranspiration but transpiration is significant due to deep root systems (Hall, 2001). Crop coefficients reach a maximum at the beginning of this period and remain relatively constant throughout due to the closure of the crop canopy, which “fixes” the effective leaf area for transpiration until senescence (Allen *et al.*, 1998). At late-season, leaf senescence occurs causing a decrease in stomatal water transport, ground cover, and K_c (Hall, 2001).

Studies that determine K_c for cotton are summarized here. Allen *et al.* (1998) provides various tables and figures representing the characteristics of K_c from an aggregation of lysimeter data and Food and Agriculture Organization of the United Nations - Irrigation and Drainage Paper No. 56 (FAO-56) ET_o estimates. Mid-season K_c values typically range from 0.9 to 1.2 (Allen *et al.*, 1998). In Texas, the initial stage extends approximately 30 days, the development stage 50 days, the mid-season stage 55 days, and the late stage 45 days (Allen *et al.*, 1998). For

an irrigated cotton crop under normal growing conditions, the typical K_c for the initial and development stages vary widely depending on rainfall and irrigation frequency, the mid-season stage K_c is 1.15 to 1.2, and the end stage K_c is 0.4 to 0.5 (Allen *et al.*, 1998).

In the humid subtropical environment of Griffin, Georgia, K_c values were calculated for irrigated DeltaPine 555 BR/RR cotton in 2005 in a sandy soil (Suleiman *et al.*, 2007). ET_c was estimated using soil moisture and leaf area index measurements, and ET_o was estimated for a grass surface using the Priestly-Taylor method (Suleiman *et al.*, 2007). For the 90 percent irrigation threshold, the initial stage occurred from sowing to 10 percent ground cover (30 days), the development stage extended until flowering began or at about 80 percent ground cover, the mid-season stage extended 46 days, and the late stage began when about 90 percent of the bolls had opened (Suleiman *et al.*, 2007). The observed K_c values were 1.12 and 0.99 for the first and second part of the initial stage, 1.15 to 1.2 for the mid-season stage, and 0.5 to 0.7 for the late season stage (Suleiman *et al.*, 2007).

In a semi-arid region of Lebanon, the Bekaa Valley, K_c values were computed for cotton in 2001 and 2002, with the cotton crop (AgriPro AP 7114) drip irrigated after emergence (Karam *et al.*, 2006). ET_c was determined using two drainage lysimeters containing a clay soil, and ET_o was measured using two drainage lysimeters with a rye grass surface (Karam *et al.*, 2006). The initial stage corresponded with sowing to squaring, the mid-season stage with first bloom to first open boll, and the late season stage with early boll loading to mature bolls (Karam *et al.*, 2006). The average K_c values were 0.58 for the initial stage, 1.10 for the mid-season stage, and 0.83 for the late season stage (Karam *et al.*, 2006).

In northern Syria, K_c values were determined for fully irrigated cotton from 2004 to 2006 on a fine clay soil (Farahani *et al.*, 2008). K_c values were adjusted for the local climate based on FAO-56 procedures from Allen *et al.* (1998) (Farahani *et al.*, 2008). The average initial stage

was 39 days long and corresponded with emergence to 10 percent ground cover, the development stage lasted 34 days and terminated with peak bloom, the mid-season stage extended 30 days and ended at the occurrence of the first open bolls, and the late stage was 39 days long and terminated at second picking (Farahani *et al.*, 2008). The average initial stage K_c was 0.29, the mid-season stage was 1.05, and the end stage was 0.66 (Farahani *et al.*, 2008).

In the tropical wet conditions of Coimatore in southern India, K_c values for cotton (MCU-9) were determined for six seasons within the period of 1976 to 1985 (Mohan and Arumugam, 1994). The cotton crop was irrigated at 25 percent maximum allowable depletion (Mohan and Arumugam, 1994). ET_c was measured using gravimetric lysimeters with a reconstructed clay loam soil, and ET_o was estimated for a grass surface using the FAO-24 method (Mohan and Arumugam, 1994). According to the K_c plot described in Mohan and Arumugam (1994), the average K_c values were 0.46, 0.70, 1.01, and 0.39 for the initial (day 0 to 24), development (day 25 to 59), mid-season (day 60 to 144), and late season (day 145 to 190) stages, respectively. A linear trendline was also derived for each stage (Mohan and Arumugam, 1994). The values of a_0 (y-intercept) were 0.385, 0.193, 2.207, and 1.466 for the initial, development, mid-season, and late season stages, respectively; the values of a_1 (slope) were 0.005, 0.012, -0.012, and 0.007; values of R^2 (coefficient of determination) were 0.471, 0.804, 0.898; and values of s_{yx} (standard error) were 0.073, 0.094, 0.077, and 0.040 (Mohan and Arumugam, 1994).

The studies in Georgia, Lebanon, Syria, and India, produced mid-season K_c values in the range of 0.8 to 1.2 (Suleiman *et al.*, 2007; Karam *et al.*, 2006; Farahani *et al.*, 2008; Mohan and Arumugam, 1994). K_c values for the initial and mid-season stages were highest in Georgia (and were closest to the mid-season stage FAO-56 value (Allen *et al.*, 1998)) and lower in decreasing order for Lebanon, Syria, and India. For the late season stage, Lebanon produced the highest K_c values followed in decreasing order by Syria, Georgia, and India. Many factors can cause

discrepancies when comparing K_c between different studies such as the irrigation method, ET_c method, ET_o method, crop variety, planting date, soil characteristics, growth stage designations, etc. Until more standardized methods, such as those prescribed by the SREE, are adopted and more areas are represented, K_c values should be considered as representative of the unique methodologies of derivation rather than as universally comparable.

Studies that determine basal crop coefficients (K_{cb}) – the ratio of ET_c to ET_o under conditions when the soil surface is dry but the soil subsurface contains enough water to allow full transpiration (Allen *et al.*, 1998) – are reviewed here. Since K_{cb} only considers crop transpiration, it is similar to K_c when the soil is dry or when the crop canopy is closed. Allen *et al.* (1998) reported typical K_{cb} values for irrigated cotton under normal growing conditions as 1.10 to 1.15 for the mid-season stage and 0.4 to 0.5 for the end season stage.

Howell *et al.* (2004) determined K_{cb} values for cotton at Bushland, Texas, in the steppe climate of the Northern Texas High Plains during 2000 and 2001 for a Pullman clay loam soil. The “FULL” irrigation treatment employed irrigation at a water deficit of approximately 50 cm (Howell *et al.*, 2004). ET_c was measured using two weighing lysimeters, and ET_o was estimated using the FAO-56 procedure (Howell *et al.*, 2004). The average adjusted K_{cb} values for both years were 0.15, 1.23, and 0.20 for the initial, mid-season, and late season stages (Howell *et al.*, 2004).

In the arid climate of Maricopa, Arizona, K_{cb} values were determined for irrigated cotton (DeltaPine 20) in 1993 and 1994 on a sandy loam soil (Hunsaker, 1999). K_{cb} values were determined for cotton irrigated at 50 and 55 percent allowable depletion (Hunsaker, 1999). ET_c was calculated using a soil water balance equation, and ET_o was estimated using a modified Penman method (Hunsaker, 1999). The initial stage was 35 days, the development stage 50 days, the mid-season stage 20 days, and the late season stage 33 days (Hunsaker, 1999). The K_{cb}

values for these stages were 0.23, 0.23 to 1.30, 1.30, and 1.30 to 0.40, respectively (Hunsaker, 1999).

A similar study to Hunsaker (1999) was conducted in the same region during 2002 and 2003 for DeltaPine-458 on sandy loam soil (Hunsaker *et al.*, 2005). Irrigation was performed on the day after total water depletion surpassed 43 percent (Hunsaker *et al.*, 2005). ET_c and ET_o were determined using FAO-56 procedures (Hunsaker *et al.*, 2005). The K_{cb} values reported for 2002 were 0.15 for the initial stage (35 days), 1.20 for the mid-season stage (46 days), and 0.52 for the end stage (length not available) (Hunsaker *et al.*, 2005).

In central Arizona, K_{cb} values for irrigated cotton (DeltaPine 77) were compared to Normalized Difference Vegetation Index (NDVI) data (NDVI can be used to estimate plant health (NOAA, 2007)) for 1990 and 1991 on a Trix clay loam (Hunsaker *et al.*, 2003). ET_c was determined using soil moisture measurements input into a water-balance equation, and ET_o was estimated using the FAO-56 method (Hunsaker *et al.*, 2003). In 1990, K_{cb} values were around 0.2 during emergence, 1.1 to 1.3 around day 90, after planting when canopy closure was almost complete, and decreased to around 0.7 to 0.5 by day 150 (Hunsaker *et al.*, 2003). In 1991, K_{cb} values were around 0.15 during emergence, 1.1 to 1.3 around day 90, and decreased to around 0.7 to 0.6 by day 150 (Hunsaker *et al.*, 2003).

2.4 Irrigation Scheduling

This study will determine K_c values to improve irrigation scheduling – the combined term for irrigation frequency and irrigation amount (Martin *et al.*, 1990). Irrigation scheduling is based on two main factors – soil water availability and ET_c . Falkenberg *et al.* (2007) used crop canopy temperatures measured by infrared cameras and lint yield data to assess three different cotton irrigation regimes based on 100, 75, and 50 percent ET_c in Uvalde, Texas, in 2002 and 2003 for Stoneville 4892 BG/RR cotton on a Knippa clay. ET_c was computed from ET_o derived

from an early form of the Penman-Monteith equation and K_c from the Bushland lysimeters in the Texas Panhandle (Falkenberg *et al.*, 2007). Results showed an insignificant difference in lint yield between 100 and 75 percent regimes and higher canopy temperatures and a lower yield for the 50 percent regime (Falkenberg *et al.*, 2007). The overuse of water at the 100 percent regime was attributed to the use of K_c values developed in an area with different growing conditions (Falkenberg *et al.*, 2007).

CHAPTER 3. DATA AND METHODS

3.1 Lysimeter Site and Design

Accurate, direct measurements of ET_c can be taken with a lysimeter. A weighing lysimeter is an open-topped container that can hold soil and plants and is supported by or connected to a scale mechanism. The lysimeter site (Figure 3.1 and Figure 3.2) and design (Figure 3.3) at the LSU AgCenter Northeast Research Station were described in Clawson *et al.* (2009). ET_c is the change in lysimeter mass over time, which is then converted to water depth equivalency.



Figure 3.1 Lysimeter field site at the Northeast Research Station with (a) denoting cotton fields, (b) rice fields, and a star marking the location of the lysimeters (prevailing winds are southerly) (Clawson *et al.*, 2009)



Figure 3.2 Weighing lysimeters with developing cotton crop (Clawson *et al.*, 2009)

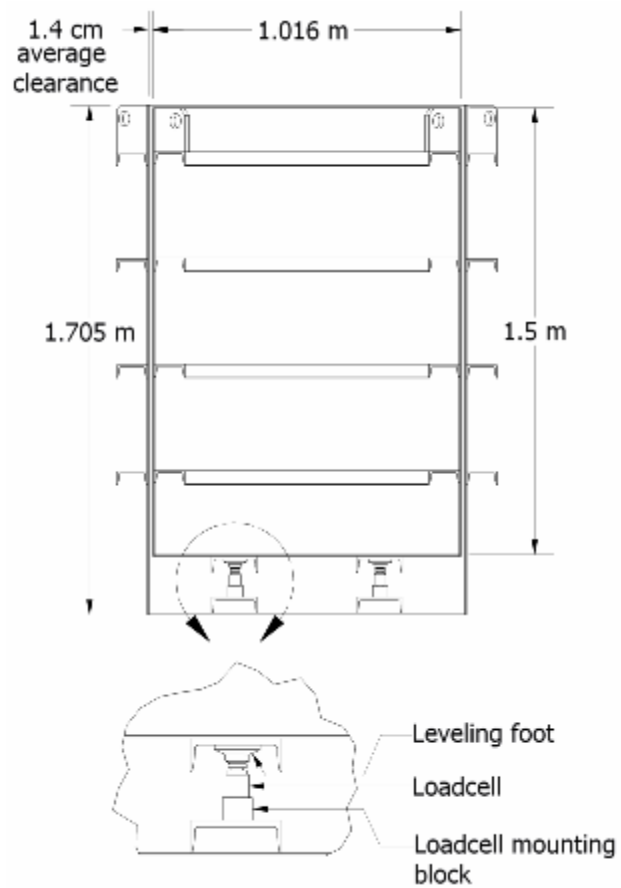


Figure 3.3 Cross-section diagram of weighing lysimeter (Clawson *et al.*, 2009)

3.2 Lysimeter Calibration

To determine the accuracy of lysimetric measurements, a calibration must be performed. In one method, lysimeter calibration involves the addition and removal of known weights on a lysimeter surface to compare applied mass to lysimeter output (Schneider *et al.*, 1998). During calibration, the lysimeter surface can be covered to prevent ET (Howell *et al.*, 1995). A wind fence can be constructed around the lysimeters to mitigate wind effects (Howell *et al.*, 1995).

Calibration allows the analysis of lysimeter performance regarding accuracy, resolution, hysteresis, and precision (Howell *et al.*, 1995). Accuracy is the error between applied mass and lysimeter output (Howell *et al.*, 1991). Resolution is the smallest mass change detectable by the datalogger (Howell *et al.*, 1991). Hysteresis occurs when points representing incremental additions of weight deviate from corresponding points of weight removal (Kirkham, 2005). Precision is the variability of lysimeter output (Howell *et al.*, 1991). Lysimeter performance can also be assessed using a linear regression analysis on calibration data (Howell *et al.*, 1995).

A lysimeter calibration performed by Howell *et al.* (1995) used applied weights ranging from 0.1 to 320 kg. Weights were added and removed according to a protocol that provided 180 data points. Each weight was measured for one minute followed by a settling period of at least one minute. Linear regression was performed with lysimeter output (mV V^{-1}) as x-values and applied mass (mm of water depth) as y-values. Results indicated a coefficient of determination (R^2) of 0.9998 for one lysimeter and 0.9991 for another. The standard errors for the two lysimeters (s_{yx}) were 1.37 and 3.38 mm. Calibration of three lysimeters in Uvalde, Texas, following a similar procedure to Howell *et al.* (1995), resulted in R^2 values of 0.9999 (Marek *et al.*, 2006). The calibration of lysimeters in Bushland, Texas, and Ismailia, Egypt, produced R^2 values of 0.9999 and s_{yx} values of 0.1 and 0.02 mm, respectively (Schneider *et al.*, 1998). As demonstrated by these studies, regression analyses should show a strong linear relationship

between applied mass and load cell output, which ensures the accuracy of lysimeter data during normal operation (Howell *et al.*, 1995).

The detailed calibration procedure and results were reported in Clawson *et al.* (2009). The following results were not reported in Clawson *et al.* (2009). R^2 values were greater than 0.999 and s_{yx} values were 0.141 mm for the north lysimeter and 0.086 mm for the south lysimeter. To convert the raw lysimeter measurements in mV V^{-1} to kg, the raw measurements were scaled using multiplier (slope) and offset (y-intercept) values. The multiplier and offset were determined from a linear regression of calibration data where applied mass plus the lysimeter mass (kg) were y-values and load cell output (mV V^{-1}) were x-values. The multiplier and offset were 1130.931 and 10.546 kg V mV^{-1} , respectively, for the north lysimeter and 1127.054 and 23.770 kg V mV^{-1} for the south lysimeter.

3.3 Lysimeter Measurements

Generally, lysimeter data are recorded by dataloggers for periods ranging from several minutes to several hours (Howell *et al.*, 1991). Howell *et al.* (1995) recommended an averaging period of at least 15 minutes to minimize wind effects. Lysimeter ET_c measurements for a certain period are typically calculated as the difference in weight between the beginning and end of that period.

Lysimeter measurements of ET_c were recorded using a Campbell Scientific, Inc. CR3000 datalogger beginning on 11 May 2007 and ending on 18 September 2007. The hand-planted cotton in and around the lysimeters was thinned on 21 May. Henceforth, representative measurements of ET_c were recorded.

The output for each load cell was measured in mV V^{-1} and converted to kg using the aforementioned multiplier and offset values. For each lysimeter, the output from each load cell and the combined output of the four load cells were measured in kg at a scan interval of 1

second. Lysimeter mass was recorded at 15-minute intervals as the mean of the 1 second measurements over the previous 15 minutes. Fifteen-minute average measurements were recorded at 00, 15, 30, and 45 minutes on the hour local time. For each day, ET_c was calculated as a positive value by subtracting the lysimeter mass in kg from 12:00 AM on the current day from the lysimeter mass in kg at 12:00 AM for the previous day. In this manner, ET_c was determined for the north and south lysimeters separately and as an average of both lysimeters. ET_c in $kg\ day^{-1}$ was divided by $1.52199047\ kg\ mm^{-1}$ to convert to units of water depth equivalence in $mm\ day^{-1}$.

Lysimeter measurements recorded at times other than 12:00 AM were used for quality control purposes. If the lysimeters were weighted at a time other than the 15-minute period recorded at 12:00 AM (*i.e.* stepped on by a person) but this event did not add or subtract mass from the lysimeter after it occurred, the daily datum was considered usable. If an event added or subtracted mass that would cause an effect on the next 12:00 AM recording, the datum for that day was considered unusable. This type of event included irrigation, daily rainfall greater than 0.025 mm (as measured using the lysimeters), pumping water from the lysimeter drains, addition or removal of lysimeter soil, and the installation or removal of instruments from the lysimeters. Such events occurred on 57 days of the 130-day lysimeter measurement period from 11 May to 18 September. These events could not simply be “cut-out” of the data by adding or subtracting mass because it could not be determined how much of the resultant change was offset by the corresponding evapotranspiration.

To maintain a similar soil water regime between the lysimeters and the surrounding field, the lysimeters were pumped after a rainfall event or irrigation as soon as the lysimeters were accessible. The lysimeters were accessible when the topsoil was dry enough to walk on without displacing it. The inside lysimeter tanks were emptied of water by pushing a plastic tube down

the vertical standpipe to the bottom of the drainage system and pumping out as much water as possible using an electric pump. Water pumped from the lysimeters was emptied directly into buckets, which were dumped into drainage channels on the perimeter of the lysimeter field to avoid overwatering plants adjacent to the lysimeters. Each lysimeter drain was pumped on the same day to avoid loss of ET_c data.

The lysimeters were routinely inspected to ensure that mass measurements were accurate. This involved checking the gap seal for leaks, clearing any debris or objects that were transferred from the outside of the lysimeters to the inside of the lysimeters, and maintaining proper datalogger operation.

3.4 Tensiometer Measurements

To monitor moisture in the soil profile, Soilmoisture Jet Fill tensiometers (Soilmoisture Equipment Corp., Goleta, California) were installed in each lysimeter and at 12 and 48 rows east and west of the lysimeters by 5 June 2007. These rows were selected because they occur in the same position in a four-row series and are located within the irrigated expanse of the lysimeter field. An exception to this was the 118 cm tensiometer for the south lysimeter, which was not installed until 18 June 2007. At each of the four locations outside the lysimeters 30, 61, 91, and 118 cm tensiometers were installed. Tensiometers were installed in the crop row approximately 20 cm apart in the center of the short axis of the field. In each lysimeter, the same series of tensiometers were installed approximately 20 cm apart and centered in the crop row.

A soil probe with a slightly larger diameter than the tensiometers was used to create holes for the tensiometers. Soil extracted from each hole was mixed with water and then poured back into the hole before each tensiometer was installed. This helped to fill any gap that might have existed between the tensiometer tip and the surrounding soil.

The tensiometers vacuum tubes were filled with a solution of water and algicide. The vacuum tube was cleared of air bubbles using a hand pump. Finally, the fluid reservoir was screwed onto the top of the tensiometer, filled with solution, and depressed several times to top-off the vacuum tube with solution. At least two days per week (sometimes less if the field was inaccessible due to wet soil conditions) the tensiometers' gauges were read and the matric potential values in centibars (cb) were recorded. Also, the reservoirs were depressed several times to top-off the vacuum tubes and, if necessary, solution was added to the reservoirs.

Because some tensiometers were not able to hold a proper vacuum, a protocol was performed to minimize tensiometer leakage. With the tensiometer in the ground, gauge threads were wrapped in Teflon tape, rubber o-rings were greased, the vacuum tube and reservoir were refilled with solution, the vacuum tube was pumped, and the gauge was set to zero while the reservoir was depressed. By 19 June 2007, this protocol had been performed on all the tensiometers and minimized, but did not eliminate, leakage. By 24 July 2007, a similar protocol was performed on leaking tensiometers wherein the rubber o-rings were replaced instead of greased.

To obtain representative measurements of ET_c , soil water levels in the lysimeter soil profile must match that of the surrounding field (Howell *et al.*, 1991). These moisture levels can be monitored using soil moisture sensors such as tensiometers. A representative soil water profile usually requires removal of water from the lysimeter drainage system (Howell *et al.*, 1991). Two anomalous situations are among those that can lead to misrepresentation of ET_c . First, the "clothesline effect" (Allen *et al.*, 1991) can influence ET_c measurements. The clothesline effect occurs when lysimeter plant height exceeds that of the surrounding plants. Larger plants receive an increased side-loading of energy, which subsequently increases ET_c . The clothesline effect can be caused by differences in fertilization, moisture, or soil compaction

between the lysimeter and the surrounding environment. To mitigate the clothesline effect, every effort should be made to maintain an even plant canopy and density.

Allen *et al.* (1991) also described how the “oasis effect” can change ET_c measurements. The oasis effect occurs when vegetation inside and near a lysimeter are wetter than surrounding vegetation. In the surrounding vegetation, excess sensible heat is created due to minimal latent heating. The sensible heat is then transferred to the lysimeter plants. This causes an increase in ET_c . To avoid this problem, adequate fetch must be maintained and adjacent fields should, ideally, have the same crop or, at least, have a similar evaporative surface as the lysimeter area. Excess soil water in the lysimeters can induce the oasis effect and increase ET_c compared to the surrounding field (Allen *et al.*, 1991). Deficient soil water in the lysimeters can cause the inverse effect.

3.5 Weather Measurements and the Standardized Reference Evapotranspiration Equation

Many methods are available for calculating ET_o , including pan evaporation, Turc radiation (Turc, 1961), Blaney-Criddle (Blaney and Criddle, 1950), and FAO-56 Penman-Monteith (Allen *et al.*, 1998). The Standardized Reference Evapotranspiration Equation (SREE) was selected for this study because of its accuracy, validity over daily intervals, transferability to various climates, and relatively simple requirements of input data (Allen *et al.*, 2005). An overview of the evolution of ET_o equations and their performance is provided below to support the selection of the SREE method.

The original Penman equation combined mass transport and energy balance equations to estimate evaporation from open water, bare soil, and turf (Penman, 1948). The modified Penman method was then developed with the incorporation of aerodynamic and surface resistance equations (Doorenbos and Pruitt, 1975). This method, however, tends to overestimate ET_o in

regions with low evaporation, and other methods also produce biased results in particular climates (Allen *et al.*, 1998).

The FAO-56 method improved upon the modified Penman and other ET_o methods. Fontenot (2004) evaluated the performance of the FAO-24 Radiation, FAO-24 Blaney-Criddle, Hargreaves-Samani, Priestly-Taylor, Makkink, and Turc methods against the FAO-56 Penman-Monteith method for determining ET_o in Louisiana. Results showed that the FAO-24 Blaney-Criddle method approximated the FAO-56 results most closely for the inland region over daily-time steps (Fontenot, 2004). The Turc method, however, was the most accurate method for the coastal and statewide regions over daily-time steps (Fontenot, 2004). Other methods performed differently according to region and time-step, demonstrating ET_o method biases in Louisiana (Fontenot, 2004).

The SREE is the ASCE-Penman-Montheith (PM) equation with standardized values for terms such as vegetation height, zero plane displacement height, and surface resistance for a short crop and a tall crop (Allen *et al.*, 2005). The SREE is

$$ET_{SZ} = \frac{0.408\Delta(Q^* - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where ET_{SZ} represents standardized reference evapotranspiration, Δ is slope of the saturation vapor pressure-temperature curve, Q^* is net radiation, G is soil heat flux density, γ is the psychrometric constant, C_n is 900 mm day^{-1} for a short crop, T is mean daily temperature, u_2 represents mean daily wind speed, e_s is saturation vapor pressure, e_a is mean actual vapor pressure, and C_d represents the drag coefficient of 0.34 mm day^{-1} for a short crop (Allen *et al.*, 2005).

The meteorological variables necessary for the calculation of ET_o using the SREE are air temperature, humidity, shortwave radiation, and wind speed (Allen *et al.*, 2005). Thus, weather

stations must be equipped with a temperature probe or thermometer, relative humidity (RH) probe or hygrometer, pyranometer, and anemometer. Temperature and humidity sensors should be located 1.5-2.5 m above the surface (Allen *et al.*, 2005). Pyranometers should be mounted so that no obstructions shade the sensor (WMO, 2006), positioned 1 m above the surface (EPA, 1990). Anemometers should be mounted 2 m above the surface or if mounted higher, mathematically adjusted to 2 m (Allen *et al.*, 2005). Data collection and processing (*i.e.*, sample, maximum, minimum, and average) must be executed according to the ET_o method and desired time interval. According to SREE guidelines, weather stations should be located downstream and over a level, uniform reference surface of well-watered, clipped grass or alfalfa with a fetch of at least 50 m (Allen *et al.*, 2005).

Daily ET_o was determined using the SREE with the input of daily total solar radiation (MJ m⁻² day⁻¹), maximum and minimum air temperature (°C), average wind speed (m s⁻¹), and maximum and minimum RH (percent). The closest and most reliable source of these weather data was the Louisiana Agrilclimatic Information System (LAIS) station on the Northeast Research Station at 31° 56' 59" latitude, 91° 14' 01" longitude, and 23.7 m above sea level (Louisiana Agrilclimatic Information System, 2009).

In 2007, this station was located 735 m from the lysimeters and was surrounded by approximately 30 m of fetch over clipped grass. This area of grass was unable to be irrigated during 2007. The temperature and RH probe was positioned 2 m above the surface. The pyranometer and anemometer were located 3 m above the surface. The wind speed was adjusted mathematically to 2 m using the following equation where u_z is the wind speed (m s⁻¹) at z_w m above the surface (Allen *et al.*, 2005).

$$u_2 = \frac{4.87u_z}{\ln(67.8z_w - 5.42)}$$

This equation assumes conditions of neutral static stability. This assumption was made because of the absence of vertical profile measurements of temperature, humidity, and wind speed. The assumption is most likely to be valid under conditions of strong winds and overcast conditions.

A portable weather station was installed approximately 34 m south of the lysimeters over the cotton crop to provide backup data should the LAIS station incur any problems. This station was outfitted with a pyranometer, temperature and RH probe, anemometer and wind vane, and a Campbell Scientific 21X datalogger (Campbell Scientific, Inc., Logan, Utah). The position of these instruments was adjusted periodically to maintain a height of 2 m above the crop canopy. During the growing season, it was determined that the LAIS station was producing faulty solar radiation data due to a malfunctioning pyranometer. Therefore, solar radiation data from the portable station and temperature, wind speed, and humidity data from the LAIS station were used as inputs into the SREE for 2007.

The previous daily meteorological variables were obtained for the period 26 May to 18 September 2007. Hourly data were also gathered for quality control purposes. If significant differences existed in hourly patterns of a variable between the LAIS station and the portable station, which could not be explained, the data for that day would not be used. If a datalogger stopped recording over an interval which affected the daily values of interest, those data would not be used. If any otherwise anomalous values occurred (*e.g.* RH over 100 percent) or data were missing, data for that day were discarded.

For every day of usable meteorological data (approximately 94 percent of days from the measurement period were usable), the total solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), maximum and minimum air temperature ($^{\circ}\text{C}$), average wind speed (m s^{-1}), and maximum and minimum RH (percent) were used in the SREE to estimate ET_0 in water depth equivalency in mm day^{-1} for a

short crop (0.12 m). Calculations were performed using the Daily Reference Evapotranspiration ET_{os} , ET_{rs} and HS ET_o Calculator (Snyder and Eching, 2009).

To examine relationships between ET_o and each meteorological variable used in the SREE, scatterplots were created representing the former as x-values and the latter as y-values. The units used for meteorological variables in the SREE were preserved in the scatterplots. Meteorological variables that were recorded as maximum or minimum were compared to ET_o separately. Each scatterplot was assessed visually to determine the type and strength of the relationship.

For some end-users of the K_c values from this study, solar radiation data may not be available for the calculation of ET_o . This would disqualify physically-based ET_o methods for estimating ET_o . However, an empirical method that only relies on the meteorological variable of temperature can be used. Monthly ET_o was estimated using an adjusted form of the empirical method for PE developed by Thornthwaite (1948) (Willmott *et al.*, 1985). Monthly E^0 was calculated for May to September 2007. Monthly ET_o for June to August was calculated as the sum of daily ET_o for each month. When a day of missing data was encountered, the average of the previous day and the next day was used as the daily ET_o .

3.6 Cotton Establishment, Management, and Measurement

Cotton seed was planted in the lysimeter field with a four-row planter on 5 May 2007. DeltaPine 555 BG/RR was used because it had been the predominant cotton variety grown in northeastern Louisiana in recent years. The lysimeters and the four-row adjacent area that could not be accessed by the planter were hand-planted on the same day. Hand-planting was performed by digging a slot about 5 cm deep in the top of a row with a flat-blade shovel. Several seeds were dropped into the bottom of the slot for each blade length. Temik was applied at 5.60 kg ha⁻¹ and Terraclor at 11.21 kg ha⁻¹. The hand-planted seeds were then covered with soil.

Additional seed was planted on 10 May because an insufficient number of seeds previously planted failed to germinate. Water was poured across the hand-planted area almost every day until 24 May. On 21 May, cotton plants in the hand-planted area were thinned to approximately 10 plants m⁻¹ to match the plant density of the surrounding field. On 22 May, one plant was transplanted in the north lysimeter.

The lysimeter field including the lysimeters was treated with herbicides, insecticides, and plant growth regulators throughout the growing season with a crop sprayer. The lysimeter field was fertilized with 127 kg ha⁻¹ of urea-ammonium nitrate-ammonium thiosulfate solution (30-0-0-2 N-P-K-S) on 5 June 2007 with a four-row implement. The lysimeter cotton plants and nearby plants inaccessible to the implement were fertilized by hand the same day. Fertilizer was applied to the lysimeter area by opening a slot in the crop row approximately 5 cm from the plants. Fertilizer was added to the slot using a syringe and the slot was covered with topsoil. Weeds growing inside the lysimeters were pulled by hand and left on top of the lysimeter surface. Farm equipment never passed directly over the lysimeters.

The lysimeter field was irrigated by an overhead linear-move sprinkler system during the 2007 growing season. Irrigation was applied from 72 rows east of the lysimeters to 72 rows west of the lysimeters. Irrigation was scheduled for every 5 cm of water loss as measured by the average of the north lysimeter and the south lysimeter. If the cotton crop began wilting, large cracks in the soil developed, or the 30 and 61 cm tensiometers showed low soil water (of approximately 70 to 80 cb), irrigation was performed prior to 5 cm of water loss. Irrigation was initiated by leaving the irrigation system centered at 72 rows west of the lysimeters and applying approximately 5 cm of water. The span was moved east 12 rows and the same amount of water was applied. This process was repeated until the irrigation system reached 72 rows east of the lysimeter.

By late June 2007 many cotton plants in and around the lysimeters were taller than plants in the surrounding field, resulting in a clothesline effect. To address this problem, the plant growth regulator Mepiquat pentaborate (N, N-dimethylpiperidinium pentaborate) was applied to taller plants using a spray bottle or hand-boom to inhibit growth. Shorter plants near the lysimeters were stripped of fruit to promote growth and even the crop canopy. To further promote growth, foliar treatments of N (22 percent urea solution) were applied to short plants near the lysimeters at a rate of 8.41 kg ha⁻¹ on 25 July and 11.21 kg ha⁻¹ on 8 August.

Cotton growth stages can be used as indicators for changes in K_c because cotton water use is largely dependent on the growth stage of the cotton plant (Tharp, 1960). As previously noted, Howell *et al.* (2004) determined K_{cb} values for initial, development, mid-season, and late-season stages. These growth stages, respectively, corresponded to planting to first square (40-50 days), first square to first flower (FF) (40 days), FF to peak bloom (50 days), and peak bloom to harvest (28-30 days) (Howell *et al.*, 2004). Allen *et al.* (1998) expressed the growth stage lengths by number of days for cotton in Texas: initial (30 days), development (50 days), mid-season (55 days), and late season (45 days).

Growth stages recorded for this study included pre-squaring, pin-head square (PHS), match-head square (MHS), and first flower (FF). Pre-squaring plants have no square visible. PHS and MHS are determined by subjective observations of square size in relation to an actual pin-head or match-head. FF is designated after a plant has produced a flower. Peak bloom occurs when the maximum number of blooms is achieved.

Plant growth measurements such as plant height, number of main-stem nodes, internode length, nodes above white flower (NAWF), and canopy cover can also be useful for determining cotton development. Internode length is the distance between two nodes. Plant height is measured in cm as the distance from the base of the main stem at the soil surface to the tip of the

main stem. Internode length is the length between the third and fourth main stem nodes from the top of the plant or, if longer, the fourth and fifth nodes. NAWF is the number of main-stem nodes above the uppermost white flower in the first fruiting position. Canopy cover is the percentage of the soil surface that is shaded by the plant canopy. In addition to growth stages, the previous indicators of cotton growth can be used to detect changes in ET_c .

Cotton growth stages were recorded once a week during 2007. As appropriate, plant growth measurements were recorded for the same time period and interval. To select plants for assessment, six row segments were marked: four 3 m sections in the center of rows 48 west, 13 west (12 west was shorter than the surrounding field), 12 east, and 48 east of the lysimeters and two 1.5 m sections represented by the north lysimeter and the south lysimeter. For each of these segments, five plants were marked that were of an average height and healthy appearance. Because the lysimeter plants were taller than the surrounding field in 2007, weekly growth stages and plant development indicators were determined for each lysimeter and for both lysimeters instead of the six marked segments.

To determine weekly growth stages indicators, the following numerical values were assigned: pre-squaring=0, PHS=1, MHS=2, and FF=3. For each week, the average of the numerical growth stages was rounded to the nearest integer for the ten marked lysimeter plants and then considered the growth stage. Plant height, main stem nodes, internode length, and NAWF were determined by averaging values for the marked lysimeter plants.

The plant growth measure of canopy closure was recorded three times during the growing season using a camera on a boom. Overhead photographs were taken with the camera centered in the middle of the length of the lysimeter in the furrow approximately east and west of each lysimeter. Two rulers were laid perpendicular to the rows and centered on the lysimeter seal to facilitate estimation of the percent of soil surface covered by the cotton plants.

For this study, the initial growth stage was the period beginning with planting over which K_c roughly maintained a slope of 0. The development stage included the following period that exhibited a sharp increase in K_c . The mid-season began with the cessation in increasing K_c and continued as K_c remained roughly constant. Sufficient data were not available for the-late season stage. These characteristics are represented in Figure 3.4 from Allen *et al.* (1998).

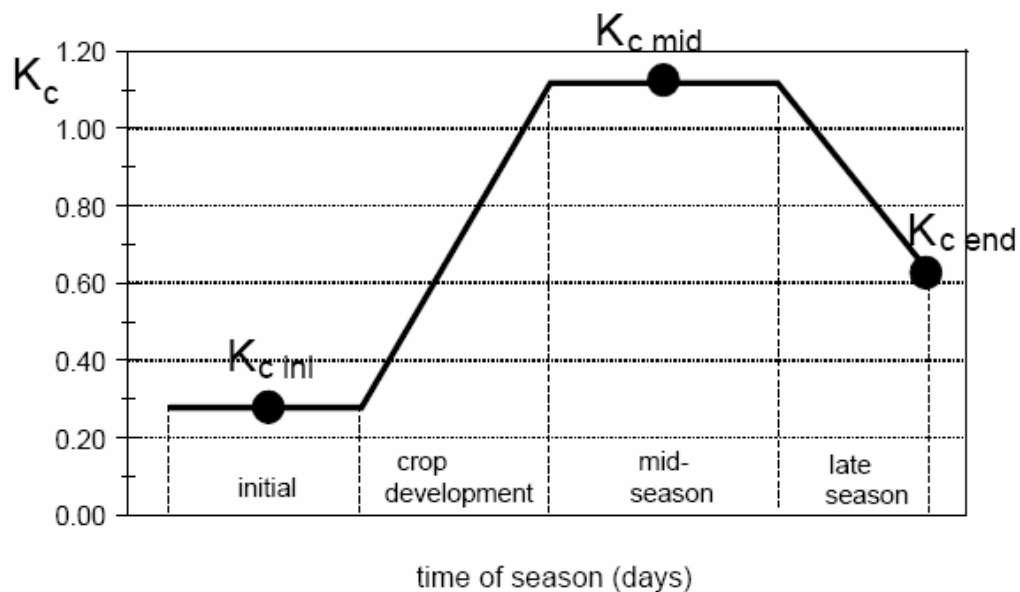


Figure 3.4 Typical K_c curve (Allen *et al.*, 1998)

3.7 Crop Coefficient Calculation

K_c was calculated by dividing daily ET_c by ET_o . Because the latter two variables have the same units, K_c represents a dimensionless ratio. K_c values were represented in three ways:

1) K_c values were averaged over the initial, development, and mid-season stages. 2) A linear trendline was fit to K_c for each stage using a regression equation where d is the day after planting.

$$K_c = a_0 + a_1 d$$

3) K_c values were compared to growth stage indicators and plant growth measurements.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Crop Evapotranspiration

Lysimeter measurements of mass were recorded from 11 May to 19 September 2007 (Figures 4.1 and 4.2). The pattern of mass change over the growing season did not differ significantly between the lysimeters. The south lysimeter, however, was about 100 kg heavier than the north lysimeter. This difference was attributed to more reconstructed soil being present in the south lysimeter (Figures 4.1 and 4.2). The sharp increases in lysimeter mass in Figures 4.1 and 4.2 occurred during irrigation and rainfall events. The rapid decreases occurred on days when lysimeter drains were pumped. The unequal distribution of water from the overhead irrigation or more water being pumped from one lysimeter than the other would sometimes cause a different rate of mass change between the lysimeters. In these cases, the lysimeter data were not used. As the growing season progressed, the rate of lysimeter mass loss became, in general,

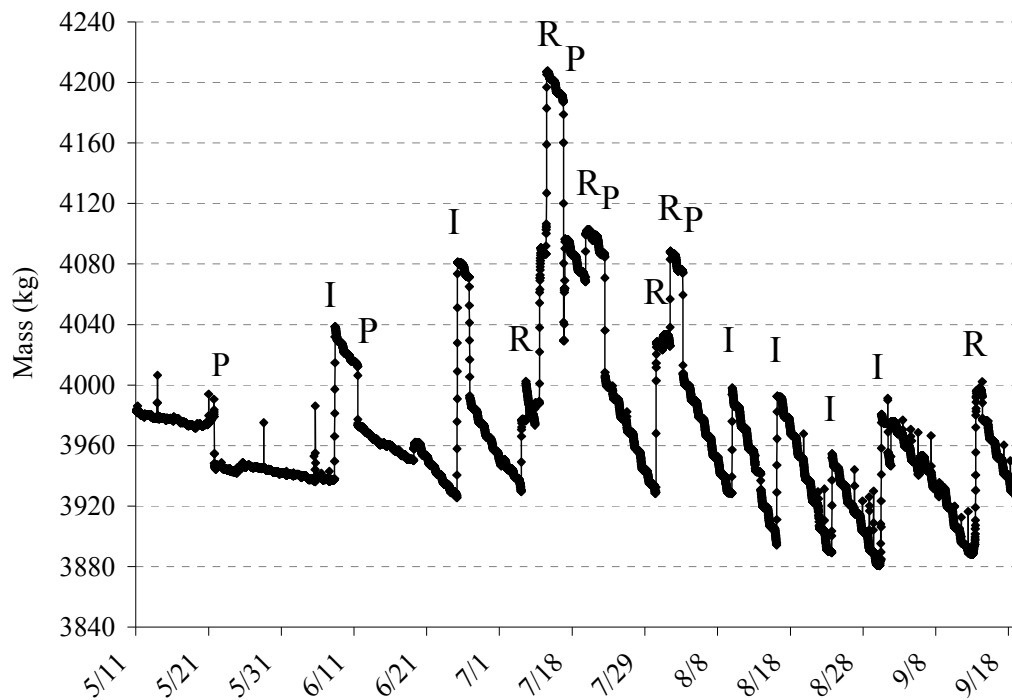


Figure 4.1 North lysimeter mass for 2007 with (I) denoting irrigation, (R) rainfall, and (P) pumping

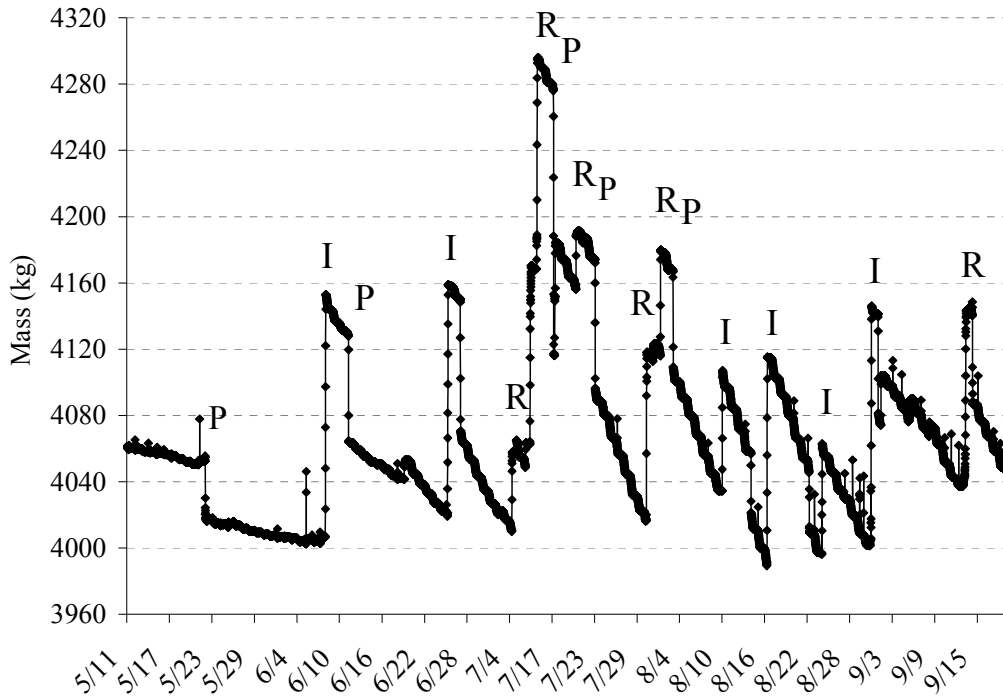


Figure 4.2 South lysimeter mass for 2007 with (I) denoting irrigation, (R) rainfall, and (P) pumping

steeper for consecutive days of undisturbed data. This was a result of increased cotton transpiration.

On a daily time scale, lysimeter mass measurements resemble a sinusoidal curve with flattened ridges and troughs. The following characteristics of mass measurements from an undisturbed lysimeter are described for an average day (Figure 4.3). From about 12:00 AM to 8:00 AM, lysimeter mass did not change significantly because plant stomata were closed in the absence of sunlight. After 8:00 AM, mass began to decrease as temperature, solar radiation, and wind speed increased. The fastest decrease occurred near 2:00 PM or 3:00 PM. After 7:00 PM, mass did not change significantly as plant stomata closed.

Minimum masses were higher than the minimum lysimeter calibration masses. The north lysimeter maximum mass was 118.28 kg higher than the maximum lysimeter calibration mass. The north lysimeter recorded masses higher than the maximum lysimeter calibration mass from

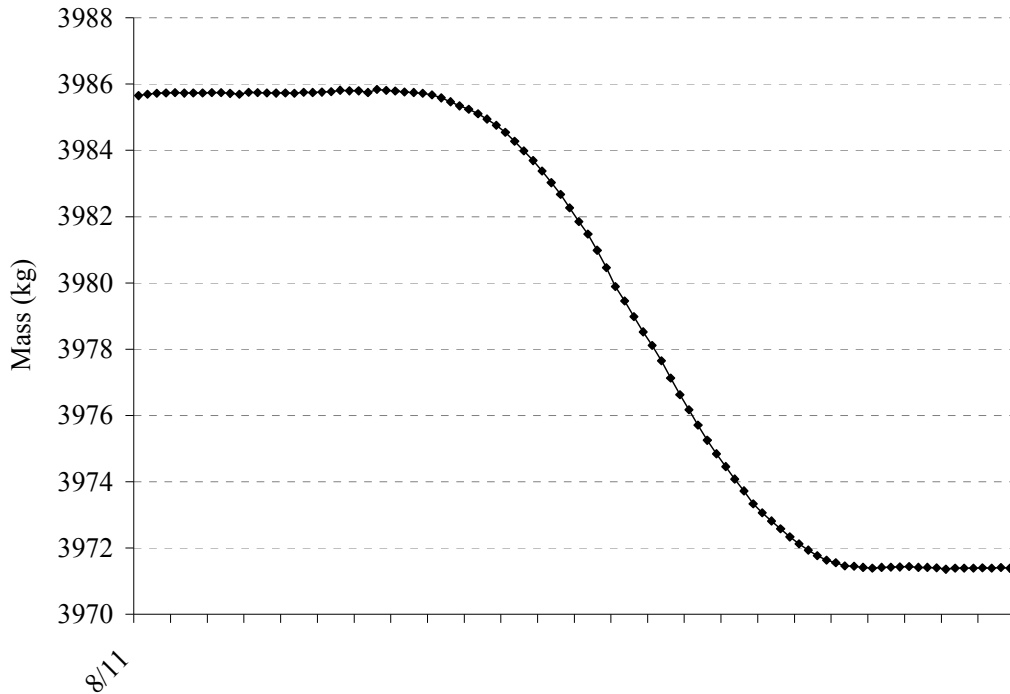


Figure 4.3 North lysimeter mass measurements on 11 August 2007

14 June to 22 June. The maximum south lysimeter mass was 169.917 kg higher than the maximum lysimeter calibration mass. The south lysimeter recorded masses higher than the maximum lysimeter calibration mass during mid- to late July and on a few occasions in early August and late September.

Mass measurements that exceeded the maximum calibration threshold were the result of the lysimeter drains not being pumped frequently enough after irrigation treatments. In these cases, the lysimeter data were used. It was assumed that measurements exceeding the calibration maximum would not suddenly become inaccurate because load cell responses were highly linear with minimal hysteresis throughout the calibration range of masses. Furthermore, days on which the lysimeter mass exceeded the calibration mass were relatively infrequent.

4.2 Precipitation

Minimal precipitation occurred during May and June at the Northeast Research Station as high pressure dominated much of the southeastern United States. However, several strong

precipitation events occurred throughout July (Figure 4.4), causing a far higher departure from normal for total monthly precipitation (Table 1.1). These precipitation events were the result of strong airmass thunderstorms and occasional frontal passages. August received its share of rainfall during a brief period at the beginning of the month due to unstable airmasses. Several precipitation events occurred throughout September, a result of airmass and frontal storms, bringing higher than normal precipitation (Table 1.1).

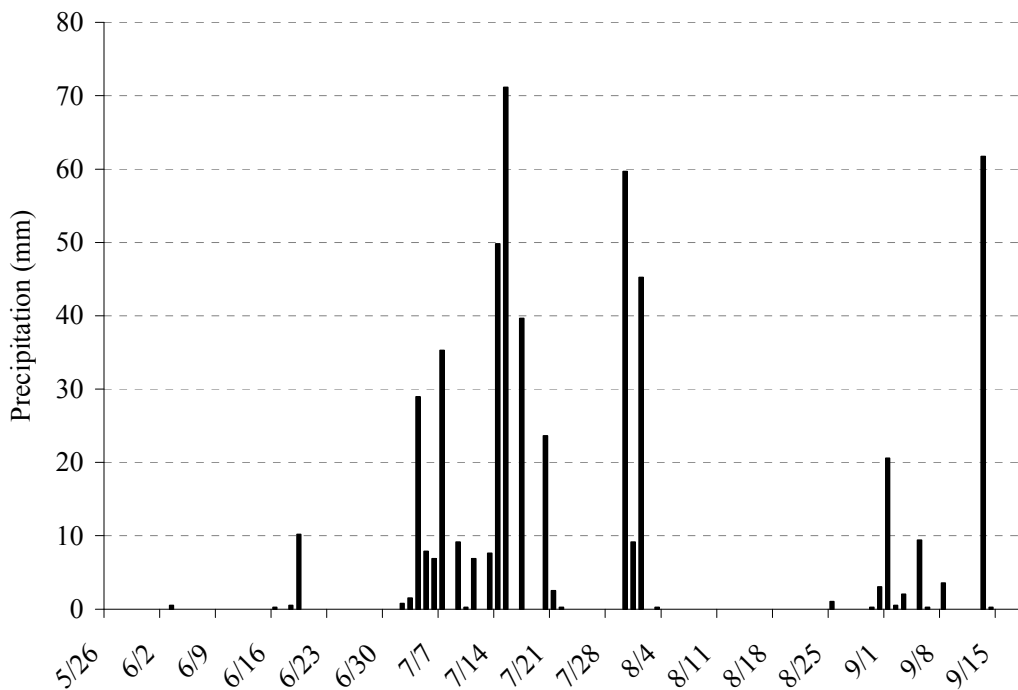


Figure 4.4 Precipitation measured using the Louisiana Agrilclimatic Information System (LAIS) weather station at the Northeast Research Station in 2007

Daily ET_c was recorded from 27 May to 18 September. The daily average ET_c was consistently low at around 1 mm day^{-1} from 27 May (and can be assumed low from the planting date of 5 May) until early June (Figure 4.5). The lowest recorded value of 0.49 mm occurred on 31 May. If valid data were available, a lower minimum value might have been recorded prior to 27 May. ET_c was low during the beginning of the growing season mainly because the cotton crop was small and did not transpire a significant amount of water (Figure 4.5). Spikes during

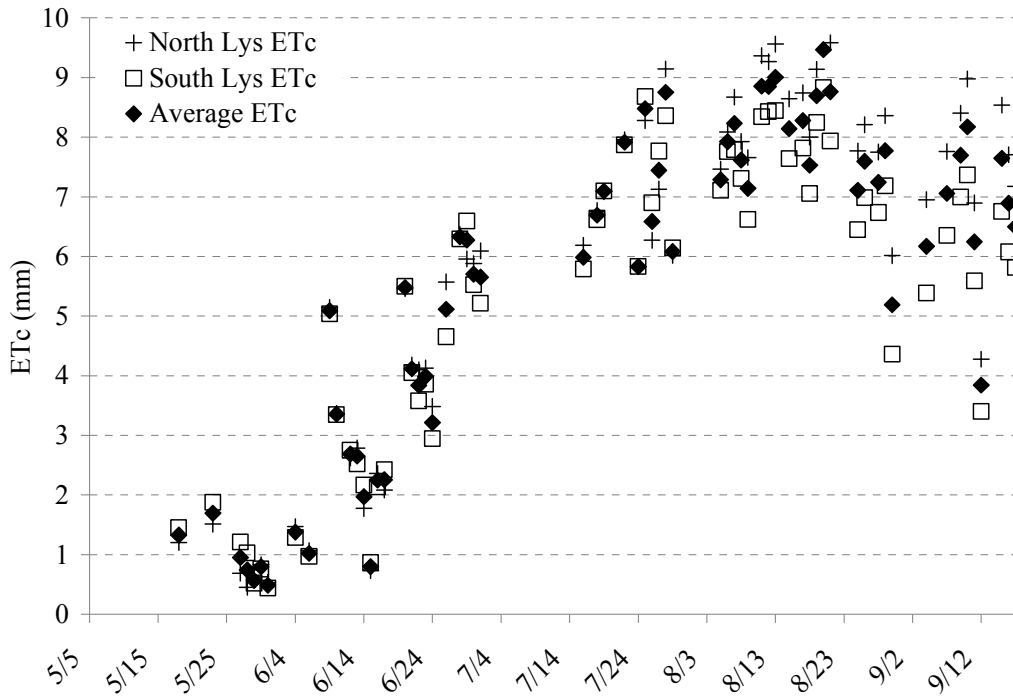


Figure 4.5 ET_c at the Northeast Research Station in 2007

this period were the result of the rapid evaporation of water following rainfall events (Figure 4.4). Daily average ET_c increased fastest from around 2 mm day⁻¹ in early June to 6 mm day⁻¹ in late June. During this period, the cotton crop developed quickly and transpiration increased. From around 6 mm day⁻¹ in mid-July, daily average ET_c increased at a slower rate until it peaked at 9.47 mm on 20 August. After mid-August, daily average ET_c decreased slowly to around 6 mm day⁻¹. After ET_c peaked in late August, it gradually decreased as solar radiation decreased in accordance with the seasonal decrease in daylight hours. The decrease in ET_c during this period could also be accounted for by maximum temperature and wind speed decreasing during the latter part of the growing season. The reduction of stomatal resistance which occurs in older leaves may have contributed to decreasing ET_c as well.

For the north lysimeter, daily ET_c ranged from 0.46 mm on 28 May to 9.58 mm on 21 August (Figure 4.5). For the south lysimeter, daily ET_c ranged from 0.44 mm on 31 May to 8.83 mm on 20 August. Daily ET_c was slightly higher for the south lysimeter than the north lysimeter

from 27 May to 1 July. During late June, daily ET_c was similar between the north and south lysimeters. After late June, the north lysimeter increasingly used more water than the south lysimeter. The largest difference in daily ET_c occurred on 15 September with the north lysimeter recording a value of ET_c 1.78 mm greater than the south lysimeter.

Although cotton plants on the north lysimeter were taller than those on the south lysimeter throughout the growing season, the daily ET_c was slightly higher for the south lysimeter than the north lysimeter from 27 May to 1 July (Figure 4.5). This may be explained by the south lysimeter containing 15 plants compared to 14 on the north lysimeter. When the cotton plants are mature, a small difference in plant density between one area and another should not theoretically change evapotranspiration. This is because the absence of a plant or plants in the less dense area decreases competition for water and nutrients, promoting horizontal growth to compensate. However, when the cotton plants are small and the leaf areas are not overlapping, the entire leaf area of the extra plant or plants in one area creates additional evapotranspiration. Crop canopy photographs from 14 June (the top photograph of Figure 4.19) show the lysimeter plants beginning to overlap and help to support this explanation.

In general, cotton plants on the north lysimeter were taller than plants on the south lysimeter, causing increased ET_c for the north lysimeter after 1 July. Furthermore, the clothesline effect was induced because plants on the north lysimeter and south lysimeter were slightly taller than the surrounding field. It may be assumed that ET_c for the lysimeters were higher than ET_c for the surrounding field.

4.3 Reference Evapotranspiration

Meteorological data from 26 May to 18 September 2007 were obtained for use in the SREE. Solar radiation measured by the portable station is shown in Figure 4.6. Although solar radiation was measured over a tall crop, it was considered as an accurate replacement for

radiation at the short crop LAIS site. The difference in the reference surface between these sites does not change the measurement of incoming solar radiation above the reference surface.

Furthermore, the two stations were close enough that the minimal change in latitude or cloud cover between them would have had a negligible influence on the receipt of solar radiation.

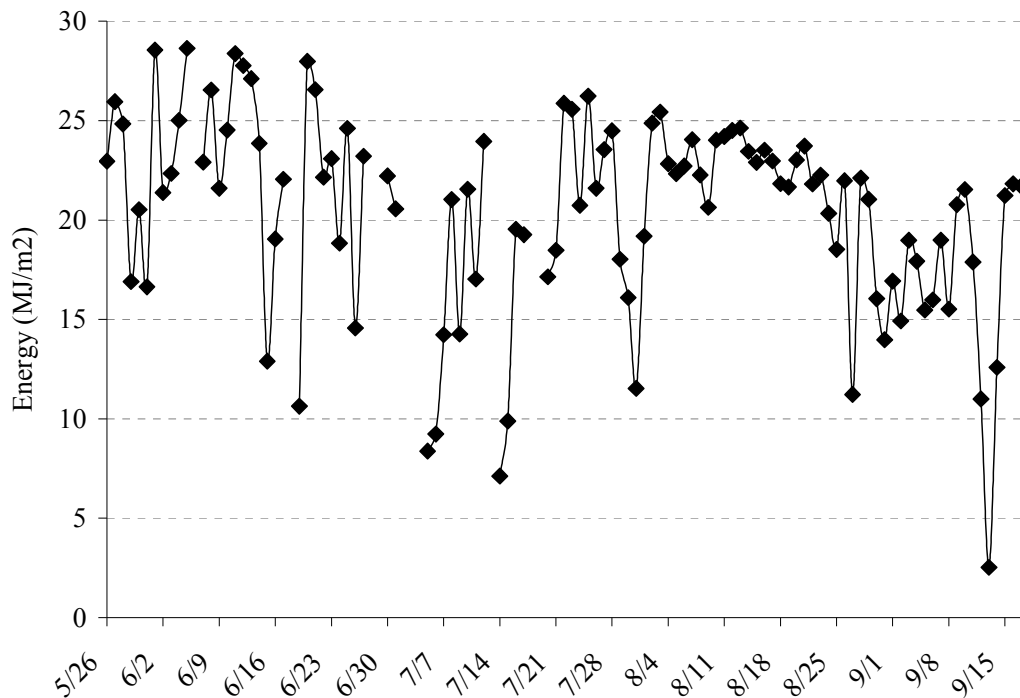


Figure 4.6 Total solar radiation in 2007

At the portable weather station, solar radiation was highest from 26 May to mid-June.

The maximum daily total solar radiation of 28.93 MJ m^{-2} occurred on 5 June rather than 21 June because of cloudier conditions during the summer solstice. This period of high observed solar radiation roughly coincides with the time of the year that experiences the most daylight hours.

According to the extraterrestrial radiation term in the SREE that determines daily solar radiation for a particular latitude ($31.9^{\circ} 56' 59''$ for the LAIS station) at the “top” of the atmosphere, the maximum solar radiation occurred on 19 June 2007. After mid-June, solar radiation trended steadily lower until mid-July and then in a few days shifted higher. The drop in solar radiation from mid-June to mid-July corresponds with a rainy period (Figure 4.4) that was

associated with cloudier conditions. After the upward shift, solar radiation again trended steadily lower until 18 September as daylight hours decreased. The minimum daily solar radiation of 2.53 MJ m^{-2} occurred on 13 September.

Maximum temperature at the LAIS weather station increased from approximately 30°C in late May to around 35°C in mid-June (Figure 4.7). Maximum temperature then decreased slightly until late July. This period corresponded to a period of increased rainfall activity (Figure 4.4). After late July, maximum temperature increased to 40.0°C on 14 August. This peak in maximum temperature occurred later than the peak in solar radiation because of the seasonal lag in atmospheric warming. Maximum temperature then decreased continuously until 18 September as daylight hours decreased. The lowest maximum temperature recorded was 25.0°C on 13 September. Minimum temperature varied widely from late May through early June (Figure 4.7). From mid-June to 15 August, minimum temperature increased gradually from around 21°C until it peaked at 25.6°C on 6 August, 7 August, and 15 August. From mid-August

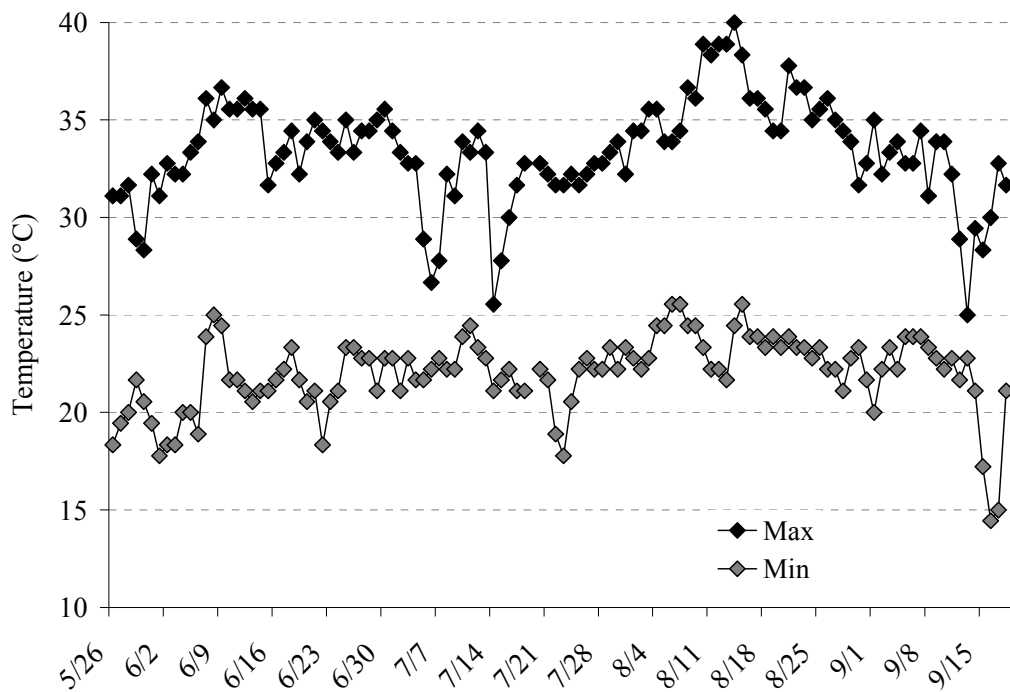


Figure 4.7 Surface temperature in 2007

to mid-September minimum temperature gradually decreased as daylight hours decreased. The lowest minimum temperature was 14.4°C on 15 August. Although maximum temperature varied more than minimum temperature, the patterns were similar.

Average daily wind speed adjusted to 2 m at the LAIS weather station (Figure 4.8) was around 2 m s⁻¹ during the first-half of the growing season and around 1 m s⁻¹ afterward. Variability in wind speed decreased over the measurement period. During the warm season, decreased storm frequency and decreased geopotential height gradients over the southern U.S. diminished surface winds. The highest average daily wind speed of 4.7 m s⁻¹ occurred on 7 June. The lowest average daily wind speed of 0.6 m s⁻¹ occurred on 13 August and 17 September.

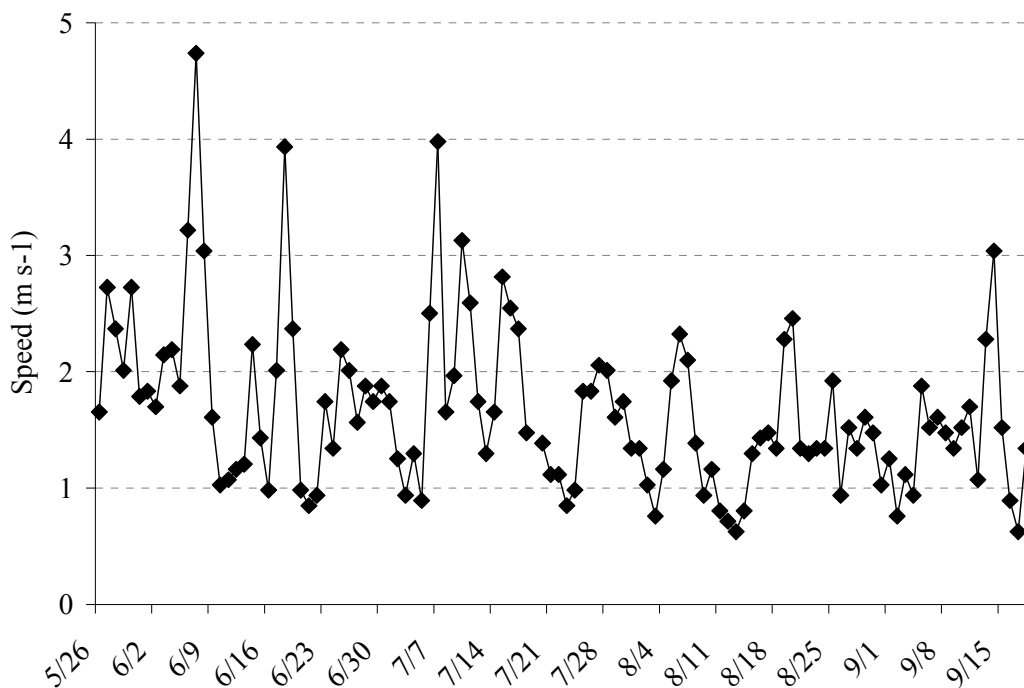


Figure 4.8 Average wind speed at 2 m in 2007

Daily maximum RH at the LAIS weather station varied from about 90 to 98 percent from 26 May to late June (Figure 4.9). Maximum RH remained high from late June to mid-July reaching 99 percent on 3 July, 14 July, and 15 July. The maximum values of RH correspond to the rainy period of the growing season. After mid-July, maximum RH trended slightly lower

until early September. This decrease in RH roughly matches an increasing trend in temperature because RH has an inverse relationship to temperature. Maximum RH then increased until 18 September during a period of lower temperatures. However, the lowest maximum RH value of 87 percent occurred on 18 September. Daily RH was approximately 40 percent \pm 10 percent from 26 May to early July. Minimum RH increased from early July to mid-July peaking at over 80 percent. After mid-July, minimum RH decreased until the lowest minimum RH of 22 percent was reached on 14 August. After mid-July, minimum RH increased to the highest value of 85 percent on 13 September. Minimum RH then decreased until 18 September. Minimum RH roughly followed the pattern of RH but in a more amplified manner.

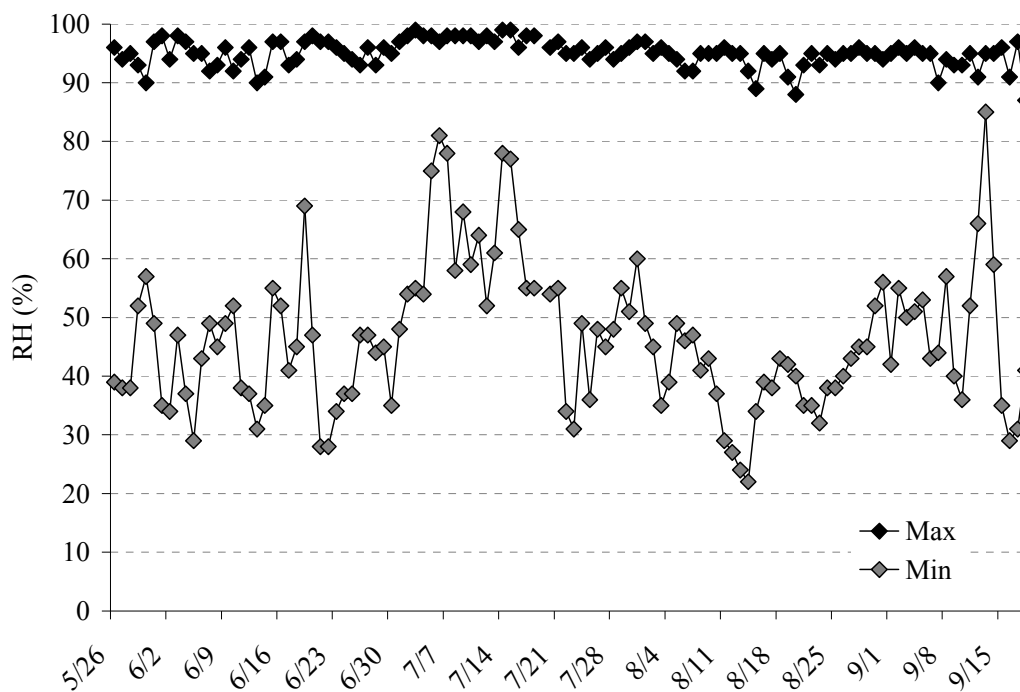


Figure 4.9 Relative humidity in 2007

Daily ET_o estimates were calculated from the previously described meteorological data for the period 26 May to 18 September (Figure 4.10). From 26 May to mid July, ET_o decreased steadily from approximately 6 mm day⁻¹ to 3.5 mm day⁻¹. The maximum ET_o of 7.07 mm occurred on 7 June. ET_o increased slightly in the latter half of July. From late July to late

August, ET_o decreased in variability and remained around 5.5 mm day^{-1} . ET_o dropped suddenly in late August and remained at approximately 4 mm day^{-1} . The minimum ET_o of 0.87 mm occurred on 13 September. The absence of irrigation at the LAIS site created an environment where soil water was limited for the grass reference surface. The fetch at the LAIS site may not have been sufficient to modify upstream winds to the reference environment. Therefore, temperature may have been higher and RH may have been lower than they should have been at the LAIS site resulting in an overestimation of ET_o . The ET_o for 2007 (Figure 4.10) does not correspond well with temperature, RH, or u individually; however, it follows the pattern of solar radiation closely (Figure 4.5).

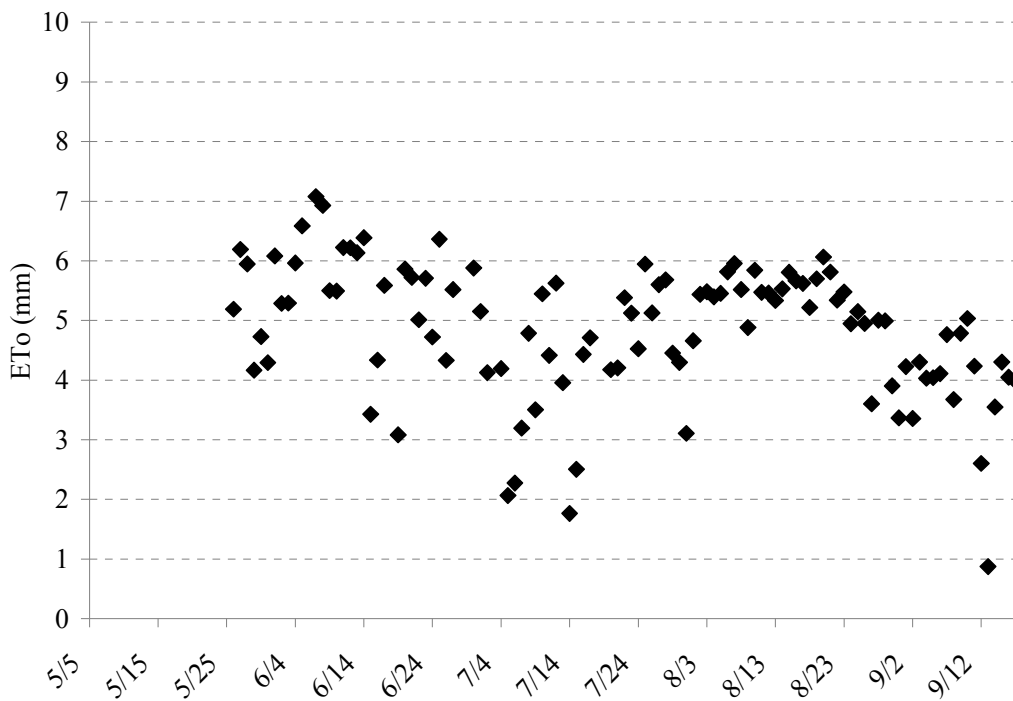


Figure 4.10 ET_o at the Northeast Research Station in 2007

According to the comparison plots, maximum and minimum temperature increased with increasing ET_o ; however, maximum temperature exhibited a stronger and steeper linear relationship than minimum temperature (Figure 4.11). Minimum temperature exercised less influence because it generally occurs during the morning when the ET_o rate is at or near 0 due to

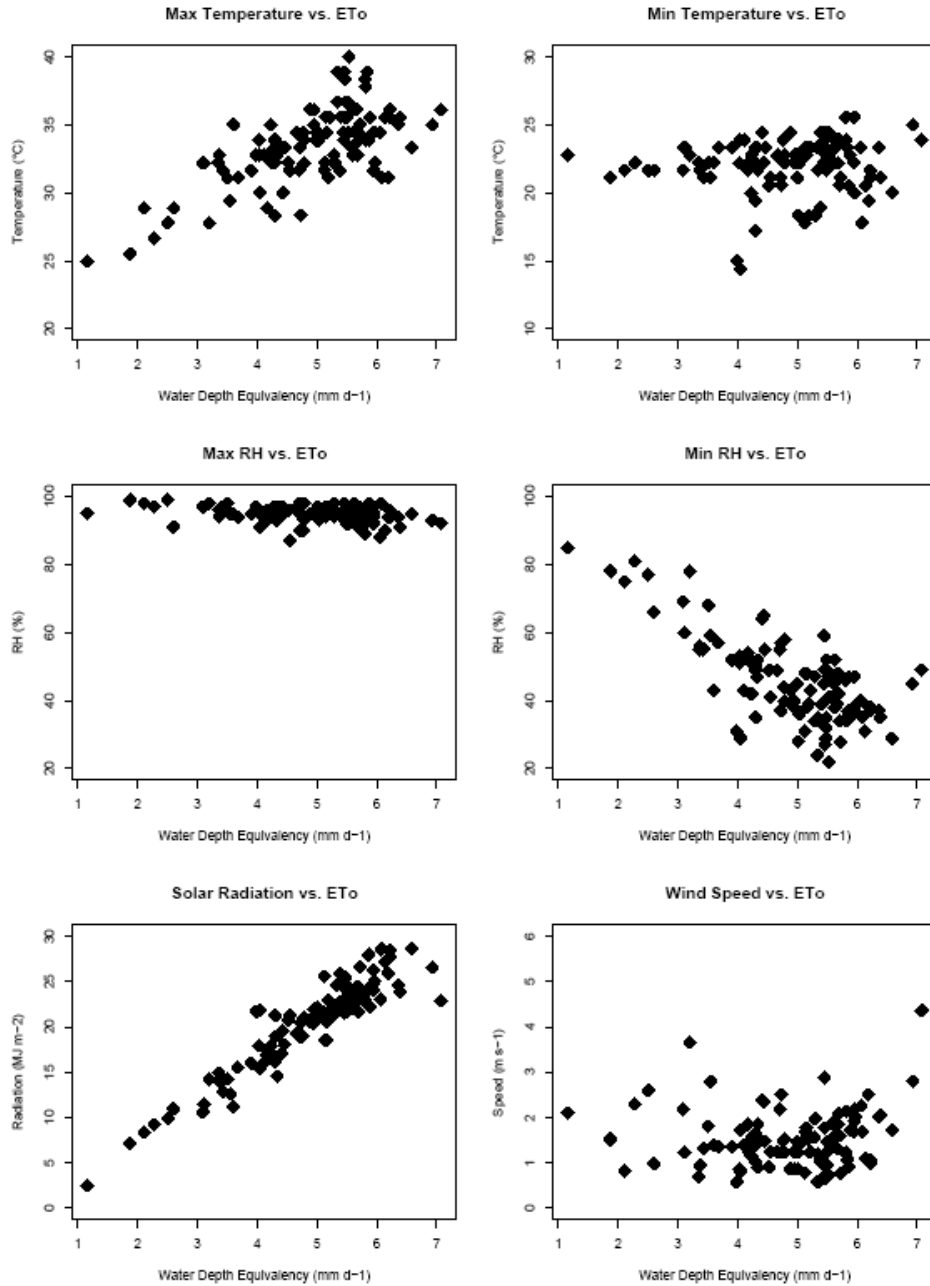


Figure 4.11 ET_0 comparison plots

decreased Q^* and increased G . Maximum RH decreased slightly as ET_0 increased. Minimum RH decreased rapidly as ET_0 increased. The relationship between maximum RH and ET_0 was weak because maximum RH typically occurred in the morning at the minimum temperature. A strong positive linear relationship existed between solar radiation and ET_0 ; however, the

relationship weakened with increasing ET_0 . The relationship was the strongest because the diurnal cycle of solar radiation triggers the opening and closing of plant stomata. The wind speed comparison plot showed the weakest relationship.

Monthly E_o' values from the adjusted Thornthwaite method were similar to monthly ET_0 values from the SREE for June, July, and August 2007 (Figure 4.12). The highest E_o' value of 167.3 mm occurred for June. E_o' decreased to 132.8 mm in July and increased to 162.8 mm in August. E_o' underestimated ET_0 by approximately 3 percent for June. For July and August, E_o' overestimated ET_0 by approximately 10 percent. This overestimation was likely due to the Thornthwaite method's inability to account for decreased solar radiation associated with storms during July and August. Despite the overestimations, these results suggest that the adjusted Thornthwaite method might be a suitable proxy for the SREE when solar radiation data are not available for northeastern Louisiana or nearby regions.

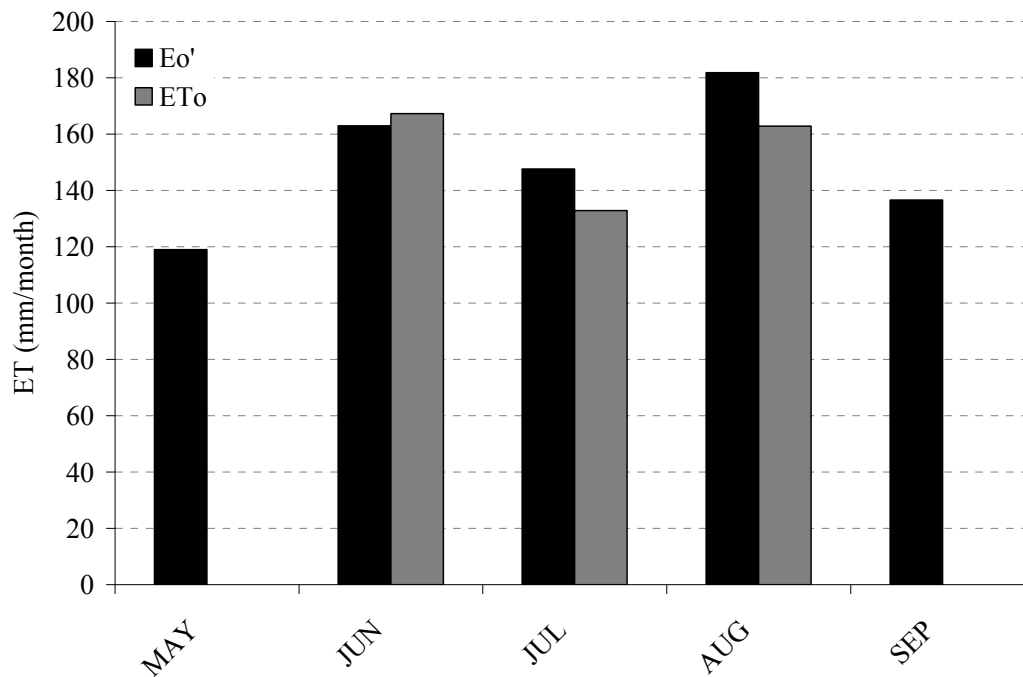


Figure 4.12 Monthly E_o' calculated using the adjusted Thornthwaite method and monthly ET_0 using the SREE

4.4 Crop Coefficients

K_c values were below 0.2 from day 0 until day 26 (Figure 4.13). The lowest K_c of 0.11 occurred on day 26. K_c values increased sharply from day 30 to day 57 and increased slightly from day 72 to day 136. The maximum K_c of 1.78 occurred on day 133. The north lysimeter K_c was similar to the south lysimeter K_c until day 49. After day 49, the north lysimeter K_c values became increasingly higher than the south lysimeter K_c values reaching a difference of over 0.2 by day 96. From day 72 onward, north lysimeter K_c values increased from about 1.4 to almost 1.6. However, from the same day forward, south lysimeter K_c values remained around 1.4.

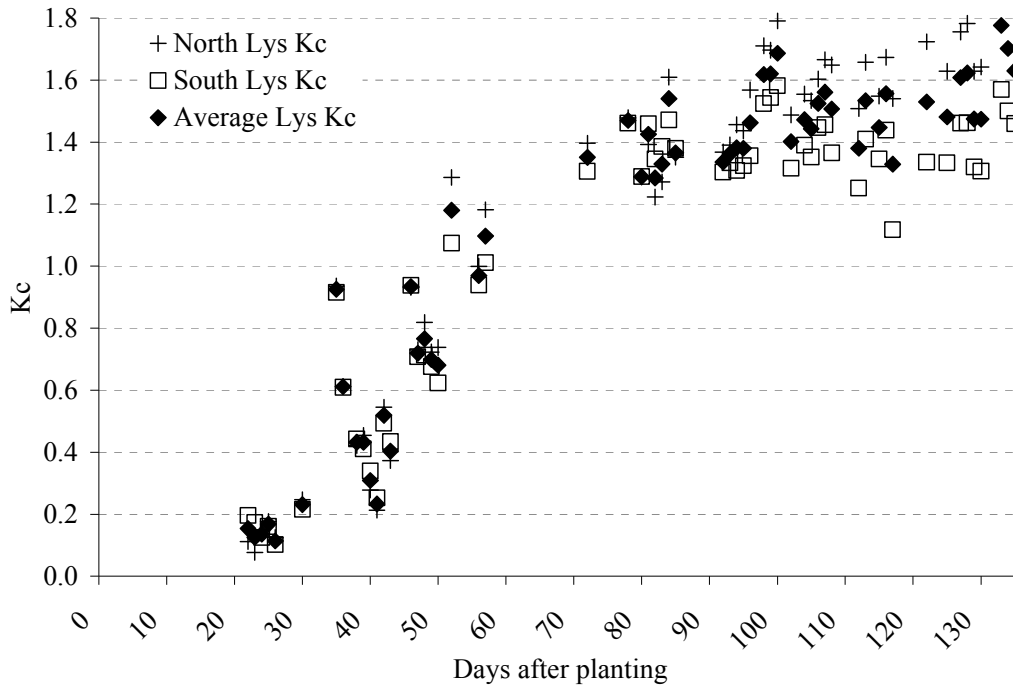


Figure 4.13 K_c values

The initial stage corresponded to day 22 to day 29 while K_c values were low (Figure 4.14). The development stage spanned from day 30 to day 69 when K_c values experienced the fastest increase. The mid-season stages extended from day 70 to day 136 when K_c values increased at a slow rate. The late season stage was not identified because of the late-maturing and late-vigorousness of DeltaPine 555 BG/RR. These properties prevented the last period of

falling K_c values which characterize the late season stage. Emergence occurred on day 7 of the initial stage. The following growth stages represent the average of both lysimeters. Pre-squaring occurred from emergence until day 40. PHS and MHS occurred on days 48 and 55, respectively, during the development stage. FF occurred on day 69, coinciding with the boundary between the development and mid-season stages.

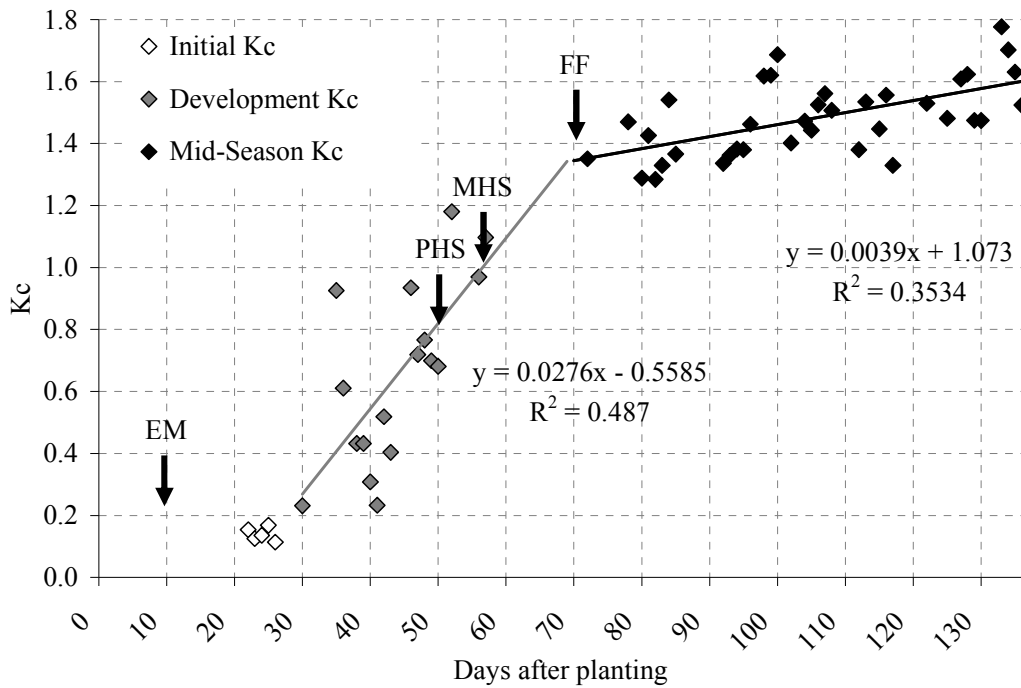


Figure 4.14 K_c values, trendlines, and growth stages (emergence (EM), pin-head square (PHS), match-head square (MHS), and first flower (FF))

PHS occurred on day 40 in the field and day 48 in the north lysimeter and the south lysimeter. MHS occurred on day 48 in the field, day 55 in the north lysimeter, and day 63 in the south lysimeter. FF occurred on day 63 in the field, day 69 in the north lysimeter, and day 76 in the south lysimeter.

Table 4.1 displays the average K_c values and regression values by stage for both lysimeters and the north and south lysimeters independently. K_c values were lowest during the initial stage and similar between the north and south lysimeters. K_c values increased during the

development stage; however, K_c values were still similar between the lysimeters. K_c values were the highest during the mid-season stage while the difference in K_c values between the lysimeters was most pronounced. Linear regression was not performed on the initial stage because sufficient data were not available. For the development stage, a_0 and a_1 values indicated a negative y-intercept and a positive slope. These values were similar between the north and the south lysimeters. For the mid-season stage, a_0 and a_1 values indicated a positive y-intercept and a smaller slope; however, the north lysimeter had a greater slope than the south lysimeter. R^2 was near 0.5 for the north and south lysimeters during the initial stage. During the mid-season stage, R^2 increased slightly for the north lysimeter and decreased substantially for the south lysimeter. The low R^2 value for the south lysimeter during the mid-season stage was the result of K_c values following a horizontal line, which is the appropriate behavior of K_c for this period. Values of s_{yx} were less than 0.01 for both lysimeters for the development stage and less than or equal to 0.0001 for the mid-season stage.

Table 4.1 Stage averaged K_c values and linear regression values of y-intercept (a_0), slope (a_1), coefficient of determination (R^2), and standard error (s_{yx}) for predicting K_c values ((N) denotes north lysimeter, (S) south lysimeter, and (NA) unavailable results)

	Initial	Development	Mid-Season
Days	0-29	30-69	70-136
Average	0.14	0.66	1.48
Average (N)	0.13	0.68	1.59
Average (S)	0.15	0.64	1.39
a_0	NA	-0.5585	1.0730
a_0 (N)	NA	-0.6800	0.8100
a_0 (S)	NA	-0.4416	1.3373
a_1	NA	0.0276	0.0039
a_1 (N)	NA	0.0300	0.0100
a_1 (S)	NA	0.0244	0.0005
R^2	NA	0.4870	0.3534
R^2 (N)	NA	0.5033	0.5965
R^2 (S)	NA	0.4593	0.0091
s_{yx}	NA	0.0073	0.0009
s_{yx} (N)	NA	0.0079	0.0010
s_{yx} (S)	NA	0.0068	0.0009

The curves of plant height as a percentage of its maximum value for lysimeter cotton followed closely to that of K_c as a percentage of its maximum value until day 86 (Figure 4.15). The main difference was that height percentages did not increase as fast during the development stage as did K_c percentages. Plant height percentages for the north lysimeter were greater than those for the south lysimeter from day 27 to day 63. After day 63, plant height percentages for the south lysimeter exceeded those for the north lysimeter until both reached 100 percent on day 107. The maximum values might have occurred later if plant height data would have been collected later.

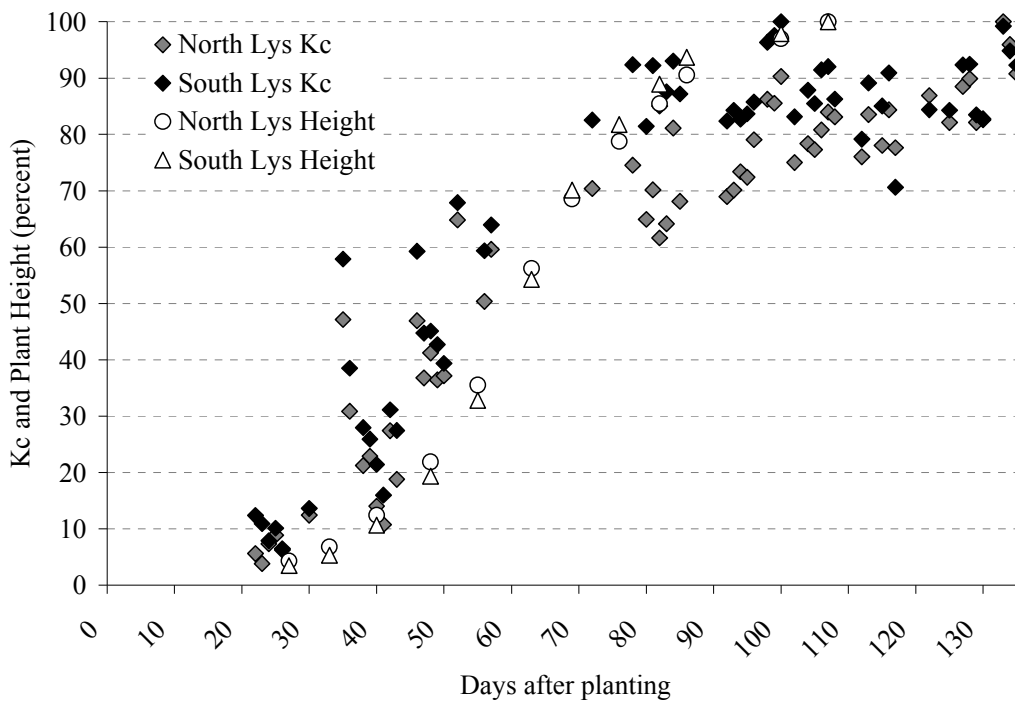


Figure 4.15 K_c as a percentage of its maximum value (1.98 for north lysimeter and 1.58 for south lysimeter) versus plant height as a percentage of its maximum value (152.6 cm for the north lysimeter and 142.6 cm for the south lysimeter)

North lysimeter plants were shorter than field plants from day 27 to day 55. After day 55, north lysimeter plants became increasingly taller than field plants. South lysimeter plants were shorter than the field plants from day 27 to day 63. After day 63, south lysimeter plants became increasingly taller than field plants. By day 107, north lysimeter plants were several cm taller than south lysimeter plants, and south lysimeter plants were several cm taller than field

plants. Lysimeter and field plants gained height from emergence until the last measurement on day 107.

Main stem nodes count as a percentage of its maximum value for the lysimeter plants roughly followed a positive linear pattern from around 10 percent on day 27 to 100 percent on day 107 (Figure 4.16). Node percentage was similar between the north lysimeter and the south lysimeter except for the period from day 55 to day 82 when the south lysimeter percentage was greater than the north lysimeter. North lysimeter plants developed less main stem nodes than field plants from day 27 to day 86. After day 86, north lysimeter plants exceeded field plants in the number of nodes. South lysimeter plants developed less main stem nodes than field plants for the entire growing season.

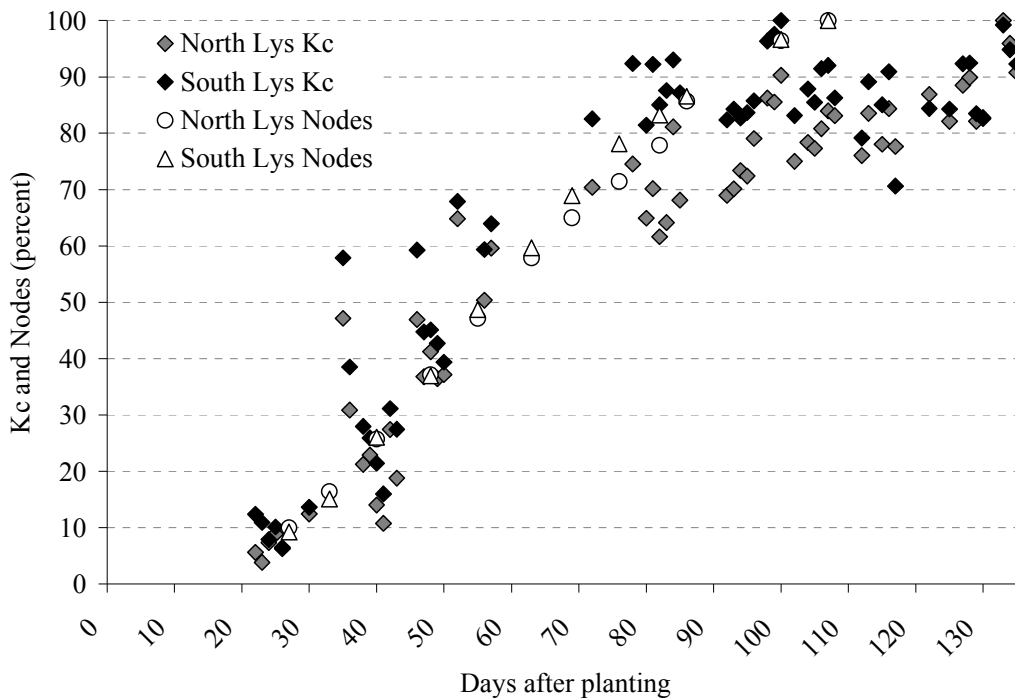


Figure 4.16 K_c as a percentage of its maximum value versus main stem nodes as a percentage of its maximum value (28.0 for the north lysimeter and 23.8 for the south lysimeter)

Internode length as a percentage of its maximum value increased rapidly for both lysimeters from around 45 percent on day 48 to 100 percent on day 63 (Figure 4.17). After day

63, internode percentage decreased to about 40 percent on day 107. North lysimeter and south lysimeter internode lengths were shorter than the field on day 48. After day 48, the lysimeter internode lengths were longer than those in the field. The south lysimeter internode lengths were longer than north lysimeter for every weekly measurement except for one taken on day 55.

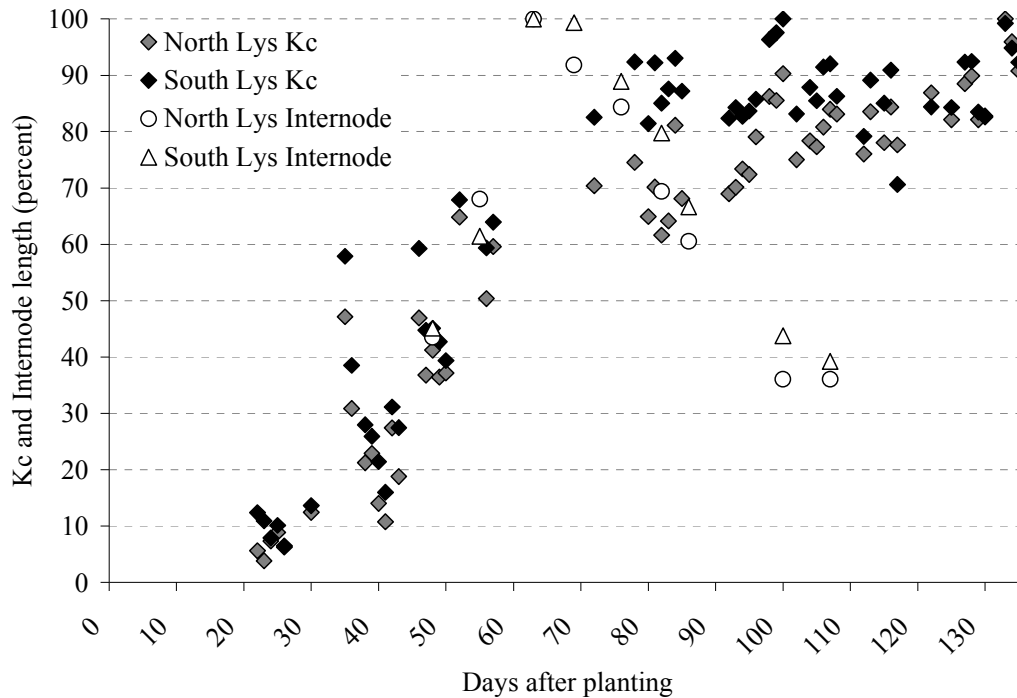


Figure 4.17 K_c as a percentage of its maximum value versus internode length as a percentage of its maximum value (3.7 cm for the north lysimeter and 3.8 cm for the south lysimeter)

Four weekly NAWF measurements were taken during the mid-season stage (Figure 4.18). The maximum NAWF was approximately 8.3 on day 82. NAWF measurements decreased to a minimum of 5 on day 107. NAWF of 5 can be used as an indicator of “cut-out” for cotton – when growth stops. North lysimeter and south lysimeter NAWF were higher than the field NAWF on day 82 and day 86. For other measurement periods NAWF was not available for both lysimeters and the field.

Figure 4.19 shows selected crop canopy photographs. The top photograph shows the crop cover at approximately 25 percent on day 40. This is 10 days after the beginning of the

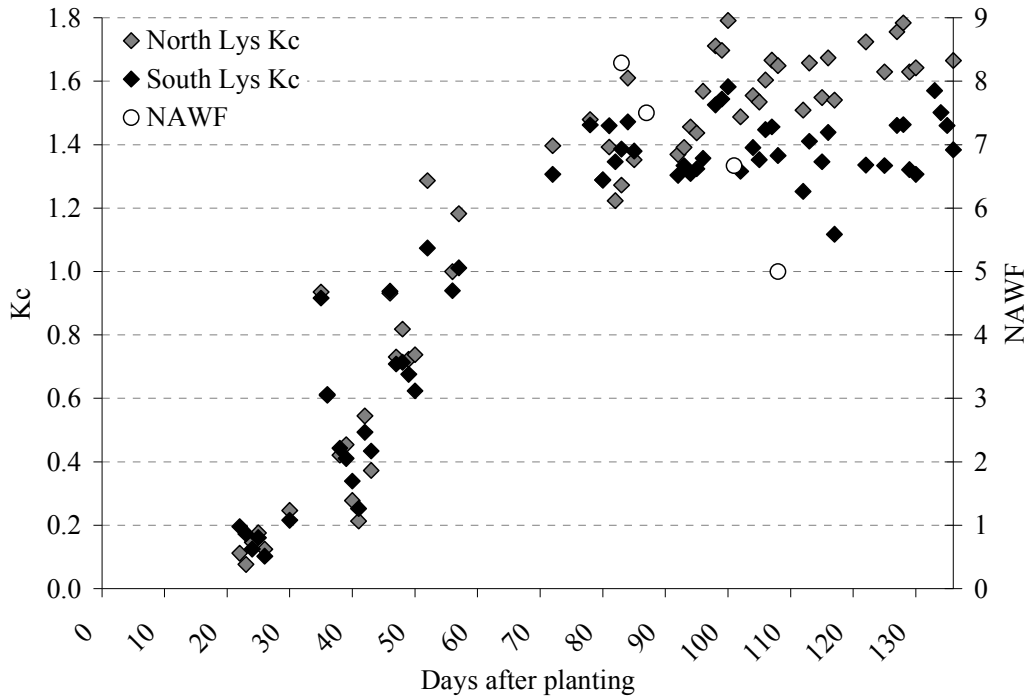


Figure 4.18 K_c versus NAWF

development stage when cotton plants were young and K_c was low. The middle photograph shows the crop cover at approximately 50 percent on day 55 during which time K_c was increasing rapidly. The bottom photograph shows the crop cover at approximately 80 percent on day 76, near the beginning of the mid-season stage. At this point, the K_c curve begins to stabilize.



Figure 4.19 Crop canopy photographs at 25, 50, and 80 percent coverage (from top to bottom)

CHAPTER 5. CONCLUSIONS

5.1 Review

This study determined daily K_c values for irrigated cotton at the LSU AgCenter Northeast Research Station in Tensas Parish, Louisiana, for 2007. K_c values were calculated by dividing ET_c by ET_o , after ET_c was measured using paired weighing lysimeters, and ET_o was estimated using the SREE for a short crop. Solar radiation data were recorded at a portable weather station near the lysimeters. Temperature, humidity, and wind speed were recorded at an LAIS weather station at the Northeast Research Station. ET_o was compared to its component meteorological variables. Also, ET_o was compared on a monthly-basis with E^o from the adjusted Thornthwaite method.

Cotton at the lysimeter site was irrigated using an overhead linear-move sprinkler system. Irrigation was applied whenever the soil water deficit exceeded 5 cm. Tensiometers were used to monitor soil water for irrigation purposes. Cotton growth stages were recorded along with measurements of plant height, number of main stem nodes, internode length, NAWF, and crop canopy coverage.

5.2 Results

Daily average ET_c was approximately 1 mm day^{-1} from 27 May to early June (Figure 4.5), with the low values occurring while the plants were small. ET_c then increased rapidly to approximately 6 mm day^{-1} by late June as plant growth developed and to 9 mm day^{-1} by late August. After late August, ET_c decreased to approximately 6 mm day^{-1} due mainly to decreasing daylight hours. During the latter half of the growing season, ET_c was higher for the north lysimeter because its plants were taller than those in the south lysimeter. ET_c for both lysimeters was likely higher than the surrounding field because of the clothesline effect.

Daily ET_o decreased from approximately 6 mm day^{-1} on 26 May to 3.5 mm day^{-1} in mid-July (Figure 4.10). After mid-July, ET_o increased to around 5 to 6 mm day^{-1} by late July and remained relatively constant until late August. ET_o decreased rapidly in late August to around 4 mm day^{-1} where it remained until mid-September. By comparing the ET_o plot (Figure 4.5) to the solar radiation plot (Figure 4.5) and examining the strength of their relationship in the comparison plots (Figure 4.11), it was evident that solar radiation mainly influenced ET_o . Monthly values of E^o calculated using the adjusted Thornthwaite method were within 10 percent of monthly values of ET_o from the SREE. Therefore, the adjusted Thornthwaite method may serve as a proxy for the SREE if solar radiation data are not available.

K_c values were less than 0.2 during the initial stage (day 22 to day 29) (Figure 4.12). Averaged K_c values for the initial stage were 0.13, 0.15, and 0.14 for the north lysimeter, south lysimeter, and lysimeter average, respectively (Table 4.1). K_c values increased rapidly from approximately 0.2 to 1.2 during the development stage (day 30 to day 69). Averaged K_c values for the initial stage were 0.68, 0.64, and 0.66, respectively. K_c values increased from approximately 1.4 to 1.6 during the mid-season stage (day 70 to day 136). Averaged K_c values for the initial stage were 1.59, 1.39, and 1.48, respectively. However, the linear regression values based on the day after planting (Table 4.1) produce more accurate K_c values than the averaged values. South lysimeter averaged K_c values and regression K_c values are likely more accurate because south lysimeter plants were closer in height to the surrounding field than north lysimeter plants.

Growth stages and plant development measurements were recorded to determine which ones corresponded to the transitions between the initial, development, and mid-season stages. PHS and MHS occurred within the development stage, but FF occurred at the beginning of the mid-season stage. Plant height as a percent of its maximum value exhibited a similar curve to K_c

values; however no feature of the height curve corresponded to changes between stages. Main stem node count as a percent of its maximum value increased linearly throughout the season and did not correspond to changes between stages. The maximum value of internode length corresponded to the beginning of the mid-season stage. NAWF of 5 occurred during the middle of the mid-season stage. Crop canopy cover at 25 and 50 percent occurred during the development stage, but the crop canopy at 80 percent occurred a few days after the initiation of the mid-season stage.

5.3 Real-World Application

The K_c values developed by this study are intended for wet July conditions for DeltaPine555 BG/RR cotton grown in a clay soil in northeastern Louisiana. However, these K_c values may also be used in nearby regions of Arkansas or Mississippi provided that the soil type and climate are similar. An easy method for comparing the climate between another region and northeast Louisiana is to examine climographs.

This example demonstrates how K_c values from this study can be used to estimate daily ET_c . A cotton farmer wants to know how much ET_c (cotton water consumption) occurred yesterday. The farmer can follow these four steps:

1) Identify the stage

- Initial stage: Day 0 - 29 after planting
(Or no squares)
- Development stage: Day 30 - 69 after planting
(Or pin-head square or match-head square)
- Mid-season stage: Day 70+ after planting
(Or after first flower, maximum internode length, or 80 percent canopy closure)

2) Determine K_c

- If the cotton was in the initial stage yesterday, use a K_c of 0.15
- Otherwise, calculate K_c using the regression equation $K_c = a_0 + a_1d$ by entering in the south lysimeter slope (a_1) of 0.0244 for the development stage or 0.005 for mid-season stage, the intercept (a_0) of -0.4416 for the development stage or 1.3373 for the mid-season stage, and yesterday's day after planting (d) (Table 4.1)

(Or use a K_c of 0.64 for the development stage or a K_c of 1.39 for the mid-season stage)

3) Determine ET_o

- Access the Louisiana Agrilclimatic Information System site at <http://www2.lsuagcenter.com/weather/Etotabledata.asp>
- Obtain yesterday's daily ET_o from the nearest station in northeastern Louisiana: Calhoun (Ouachita), Monroe (Ouachita), and St. Joseph (Tensas)

4) Determine ET_c

- $K_c \times ET_o \text{ (mm day}^{-1}\text{)} = ET_c \text{ (mm day}^{-1}\text{)}$

The steps in parenthesis are easier to execute but provide less accurate K_c values than the steps based on the day after planting. The end-user should keep in mind that the K_c values reported in this study may be overestimated due to the clothesline effect. Therefore, ET_c values derived from these K_c values may be overestimated.

REFERENCES

- Allen, R.G. and D.K. Fisher, 1990: Low-cost electronic weighting lysimeters. *Transactions of the American Society of Agricultural Engineers* 33(6):1823-1833.
- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998: FAO irrigation and drainage paper no.56: Crop evapotranspiration. <http://www.kimberly.uidaho.edu/ref-et/fao56.pdf>. Last accessed: 28 July 2007.
- Allen, R.G., I.A. Walter, R. Elliot, T. Howell, D. Itenfisu, and M. Jensen, 2005: The ASCE standardized reference evapotranspiration equation. Reston, Virginia: American Society of Civil Engineers.
- Allen, R.G., W.O. Pruitt, and M.E. Jensen, 1991: Environmental requirements for lysimeters. pp. 170-181. In Allen, T.A., T.A. Howell, W.O. Pruitt, I.A. Walter, and M.E. Jensen (eds.) *Lysimeters for Evapotranspiration and Environmental Measurements*. New York, New York: American Society of Civil Engineers.
- American Meteorological Society (AMS), 2007: Glossary of Meteorology. <http://amsglossary.allenpress.com/glossary/search?id=gale1>. Last accessed: 28 July 2007.
- Blaney, H.F., and W.D. Criddle, 1950: Determining water requirements in irrigated areas from climatological and irrigation data. Soil Conservation Service Technical Paper 96. Soil Conservation Service, U.S. Dept. of Agriculture: Washington, D.C.
- Brady, N.C., 1990: *The Nature and Properties of Soils*. New York, New York: Macmillan Publishing Co., Inc.
- Burt, C.C., A.J. Mutziger, R.G. Allen, and T.A. Howell, 2005: Evaporation research: Review and interpretation. *Journal of Irrigation and Drainage Engineering* 131(1):37-58.
- Clawson, E.L., S.A. Hribal, G. Piccinni, R.L. Hutchinson, R.V. Rohli, and D.L. Thomas, 2009: Weighing lysimeters for evapotranspiration research on clay soil. *Agronomy Journal (in press)*.
- Doorenbos, J. and Pruitt, W.O. 1975. *Guidelines for predicting crop water requirements*, Irrigation and Drainage Paper 24, Food and Agriculture Organization of the United Nations, Rome.
- Environmental Protection Agency (EPA), 1990: Meteorological Program Guidance For Regulatory Modeling Applications. Office of Air Quality Planning and Standards: Research Triangle Parks, North Carolina. <http://www.epa.gov/scram001/guidance/met/mmgrma.pdf>. Last accessed: 28 July 2007.
- Falkenberg, N.R., G. Piccinni, J.T. Cothren, D.I. Leskovar, and C.M. Rush, 2007: Remote sensing of biotic and abiotic stress for irrigation management of cotton. *Agricultural Water Management* 87(1):23-31.

- Farahani, H.J., T.Y. Oweis, and G. Izzi, 2008: Crop coefficient for drip-irrigated cotton in a Mediterranean environment. *Irrigation Science* 26(5):375-383.
- Fontenot, 2004: An evaluation of reference evapotranspiration models in Louisiana. *Master's Thesis*. Louisiana State University, Baton Rouge.
- Hall, A.E., 2001: *Crop Responses to the Environment*. Boca Raton, Florida: CRC Press LLC.
- Hanks, R.J., 1992: *Applied Soil Physics*. New York, New York: Pringer-Verlag New York, Inc.
- Howell, T.A., A.D. Schneider, and M.E. Jensen, 1991: History of lysimeter design and use for evapotranspiration measurements. pp. 1-9. In Allen, T.A., T.A. Howell, W.O. Pruitt, I.A. Walter, and M.E. Jensen (eds.) *Lysimeters for Evapotranspiration and Environmental Measurements*. New York, New York: American Society of Civil Engineers.
- Howell, T.A., A.D. Schneider, D.A. Dusek, T.H. Marek, and J.L. Steiner, 1995: Calibration and scale performance of Bushland weighing lysimeters. *Transactions of the ASAE* 38(4):1019-1024.
- Howell, T.A., S.R. Evett, J.A. Tolk, and A.D. Schneider, 2004: Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the northern Texas high plains. *Journal of Irrigation and Drainage Engineering* 130(4): 227-285.
- Hunsaker, D.J., 1999: Basal crop coefficients and water use for early maturity cotton. *Transactions of the ASAE*. 42(4): 927-936.
- Hunsaker, D.J., P.J. Pinter Jr., E.M. Barnes, and B.A. Kimball, 2003: Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index. *Irrigation Science* 22(2): 95-104.
- Hunsaker, D.J., E.M. Barnes, T.R. Clarke, G.J. Fitzgerald, and P.J. Pinter Jr., 2005: Cotton irrigation scheduling using remotely sensed and FAO-56 basal crop coefficients. *Transactions of the ASAE*. 48(4): 1395-1407.
- Karam, F., R. Lahoud, R. Masaad, A. Daccache, O. Mounzer, and Y. Rouphael, 2006: Water use and lint yield response of drip irrigated cotton to the length of irrigation season. *Agricultural Water Management* 85(3):287-295.
- Kirkham, M.B., 2005: *Principles of Soil and Plant Water Relations*. Burlington, Massachusetts: Elsevier Inc.
- Louisiana Agriclimate Information System. 2009. Station info: Northeast Research Station, LSU Agricultural Experiment Station [Online]. Available at <http://www.lsuagcenter.com/weather/stationinfo.asp?stationId=7>. (Accessed 23 Jan. 2009). LSU AgCenter, Baton Rouge, LA.

- Marek, T., G. Piccinni, A. Schneider, T. Howell, M. Jett, and D. Dusek, 2006: Weighing lysimeters for the determination of crop water requirements and crop coefficients. *American Society of Agricultural and Biological Engineers* 22(6):851-856.
- Martin, D.L., D.F. Heermann, and E. Fereres, 1990: Irrigation scheduling principles. pp. 155-203. In G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.) *Management of Farm Irrigation Systems*. St. Joseph, Missouri: American Society of Agricultural Engineers.
- Mohan, S., and N. Arumugam, 1994: Crop coefficients of major crops in South India. *Agricultural Water Management* 26(1-2):67-80.
- National Oceanic and Atmospheric Administration (NOAA), 1994: Federal Standard for Siting Meteorological Sensors at Airports FCM-S4. [http://www.ofcm.gov/siting/pdf/fcm-s4-1994\(Siting\).pdf](http://www.ofcm.gov/siting/pdf/fcm-s4-1994(Siting).pdf). Last accessed: 28 July 2007.
- National Oceanic and Atmospheric Administration (NOAA), 2007: Coastal Services Center: What is NDVI? <http://www.csc.noaa.gov/crs/definitions/NDVI.html>. Last accessed: 26 February 2009.
- Newkirk, J., 2006: National Weather Service Manual 10-1315: Cooperative Station Observations. <http://www.nws.noaa.gov/om/coop/Publications/coophandbook2.pdf>. Last accessed: 28 July 2007.
- Penman, H.L., 1948: Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 193(1032):120-145.
- Schneider, A.D., T.A. Howell, A.T.A. Moustafa, S.R. Evett, and W. Abou-Zeid, 1998: A simplified weighing lysimeter for monolithic or reconstructed soils. *Applied Engineering in Agriculture* 14(3):267-273.
- Soil Conservation Service, 1982: *Louisiana Irrigation Guide*. Alexandria, Louisiana: U.S. Department of Agriculture.
- Snyder, R. L., and S. Eching, 2009: Daily Reference Evapotranspiration ET_{os} , ET_{rs} and HS ET_o Calculator using the ASCE-EWRI (2004) method User's Guide for DYPM.EXE [Online] Available at <http://biomet.ucdavis.edu/Evapotranspiration/DYPMexe/DYPM.htm>. (Accessed 23 Jan. 2009). UC Davis, CA.
- Suleiman, A.A., C.M. Tojo Soler, and G. Hoogenboom, 2007: Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate. *Agricultural Water Management* 91(1-3):33-42.
- Taiz, L., and E. Zeiger, 1998: *Plant Physiology*. Sunderland, Massachusetts: Sinauer Associates, Inc.

- Tharp, W.H., 1960: *The Cotton Plant: How It Grows and Why Its Growth Varies*: Agriculture Handbook no. 178. United States Department of Agriculture.
- Turc, L., 1961: Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date. *Annals of Agronomy*. 12(1):13-49.
- Thornthwaite, C.W., 1948: An approach toward a rational classification of climate. *Geographical Review* 38(1):59-94.
- United States Department of Agriculture – National Agricultural Statistics Service (USDA-NASS), (2002): Census of Agriculture.
- Willmott, C.J., C.M. Rowe, and Y. Mintz, 1985: Climatology of the terrestrial seasonal water cycle. *Journal of Climatology* 5(6):589-606.
- World Meteorological Organization (WMO), 2006: Guide to Meteorological Instruments and Methods of Observation.

VITA

Sean Hribal was born in February, 1984, in Latrobe, Pennsylvania. From a young age, he was attracted to weather and, to a lesser degree, mathematics. Accordingly, he attended school at California University of Pennsylvania (CUP) to study meteorology. During the summer of 2005, Sean went storm chasing with the CUP meteorology club. He saw a tornado. Shortly afterwards, Sean participated in the National Weather Center (NWC) Research Experiences for Undergraduates (REU) in Norman, Oklahoma, where he studied temperature forecast bias correction and consensus. In fall 2007, Sean graduated from CUP with a Bachelor of Science in earth science with a concentration in meteorology. After graduating, Sean obtained employment as a customer service representative for a popular discount airfare website. This did not suit him. Owing to his rural upbringing and meteorological training, Sean developed an interest in agricultural climatology. Accordingly, he attended school at Louisiana State University to study just that. Sean is a boulderer and a proud Appalachian. His future plans include moving to Athens, Georgia, to live with his girlfriend Patti.